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OpenSees/OpenFresco Example Applications

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PEER

NSF

MTS®

NEES

KEPCO E&C

OpenFresco

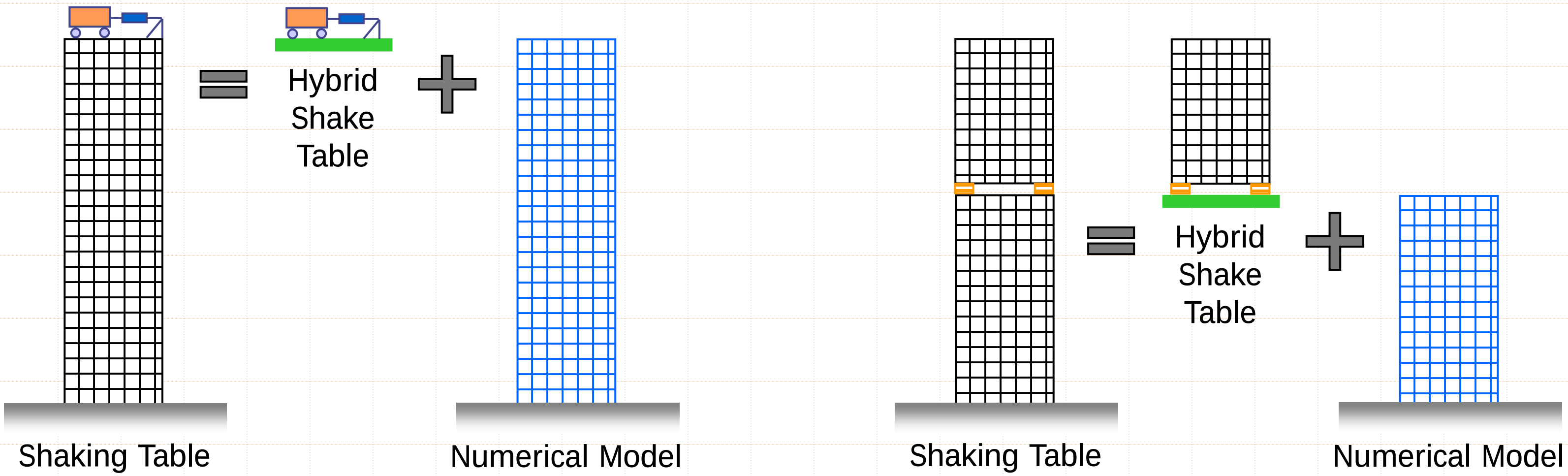
Example 1: Hybrid Shake Table

Outline for Example 1

1. Motivation
2. Midlevel Seismic Isolation
3. Hybrid Shake Table Concept
4. Test Specimen and TFP bearings
5. Test Program and Parameters
6. Preliminary Results
7. Summary & Conclusions

Motivation

- Many structures exhibit significant rate of loading effects
- Need testing to occur at or near real time
- Large systems such as tall buildings or SFSI are difficult to test on shake tables

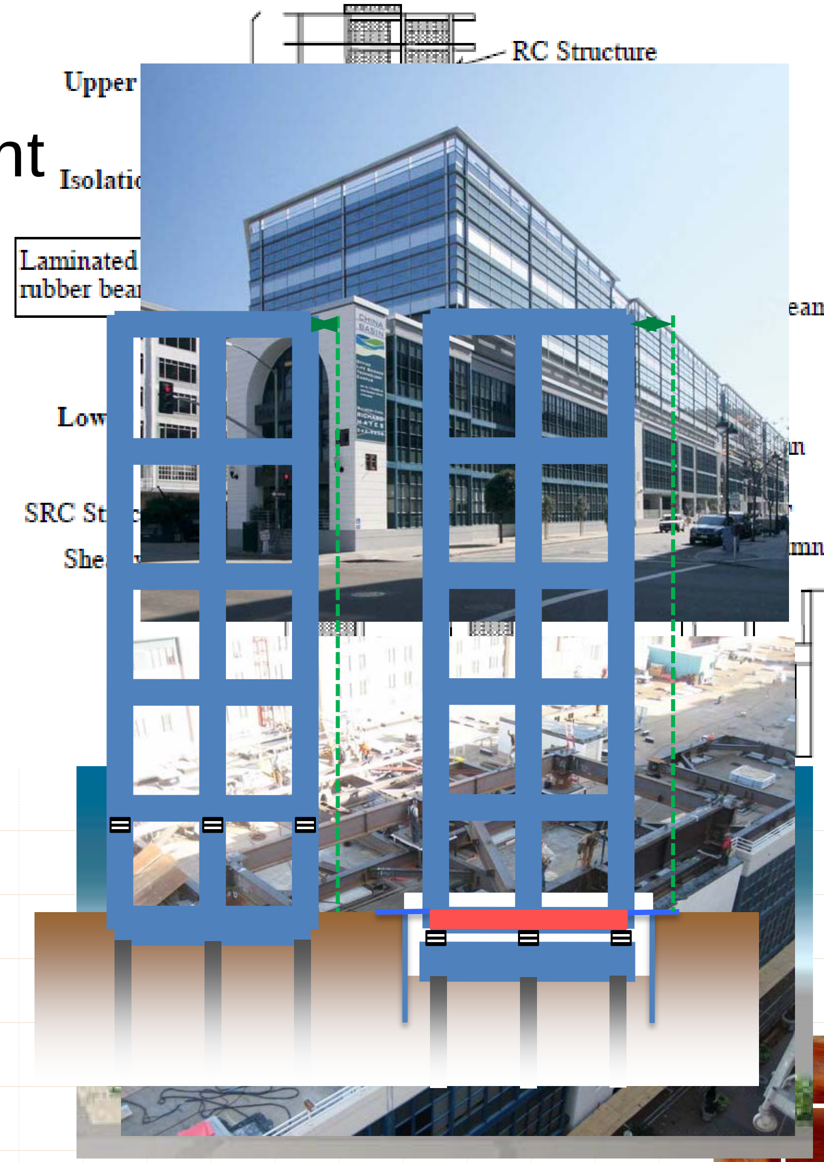


Motivation

- Enables us to perform dynamic tests of full-scale specimens without exceeding size, strength and weight limitations of shake table.
- With very little effort we can perform a wide range of parameter studies by changing the properties of the analytical portion of the hybrid model.

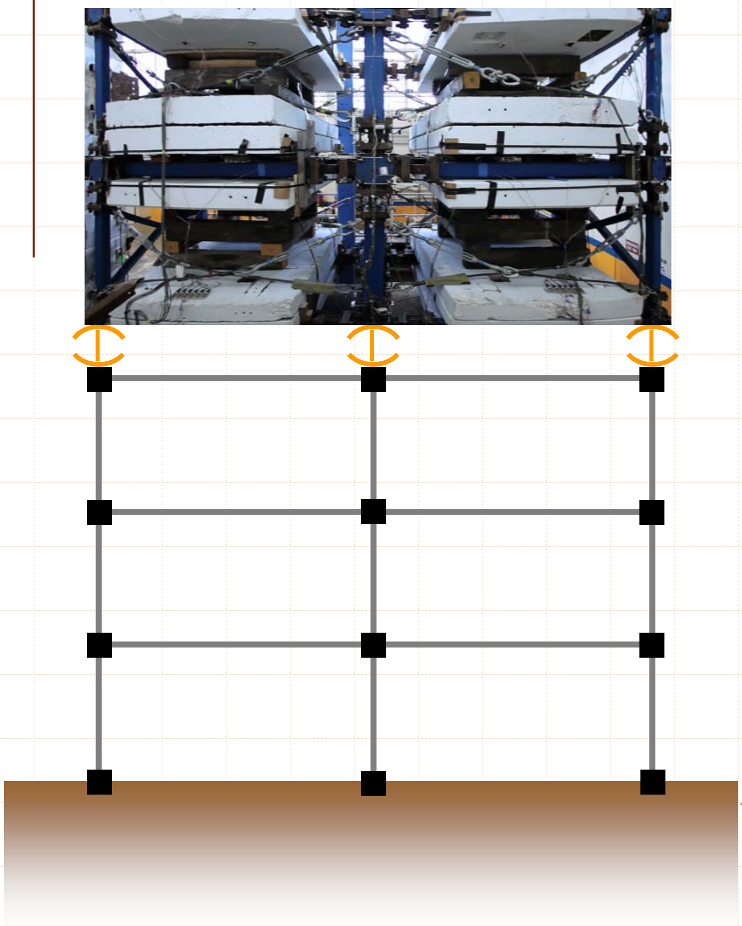
Midlevel Seismic Isolation

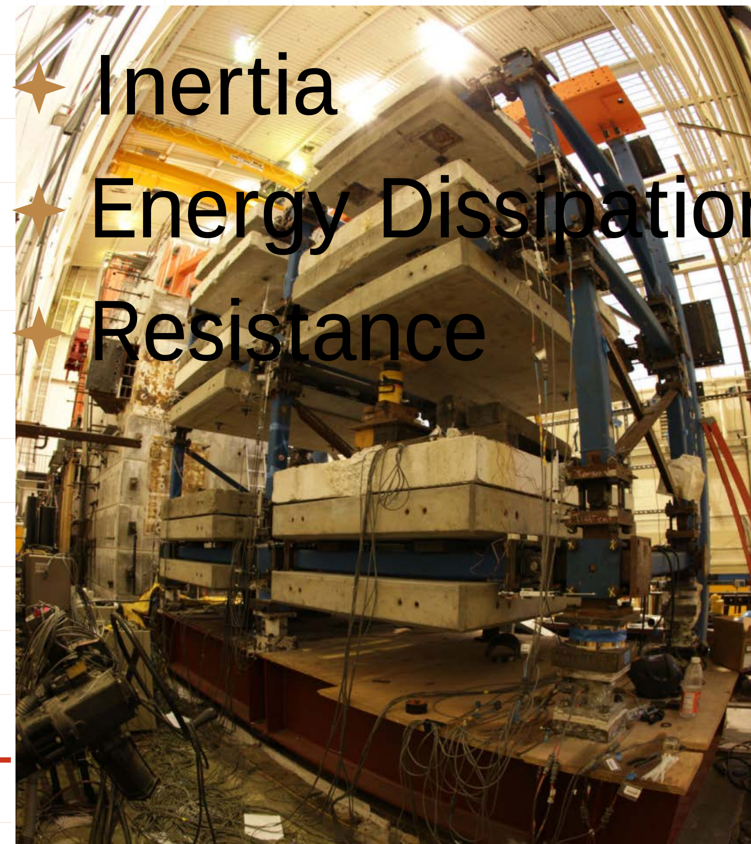
- Provide architectural flexibility
  - transitions between different structural systems
- Facilitate addition of new stories
  - minimally increase seismic demands on the existing building
  - exploit untuned mass-damper effect
- Decrease cost of isolation
  - Moat and clearance space



Hybrid Shake Table Concept

$$\boxed{\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}}+\boxed{\mathbf{P}_{\mathbf{r}}\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right)}=\boxed{\mathbf{P}\left(t\right)}$$





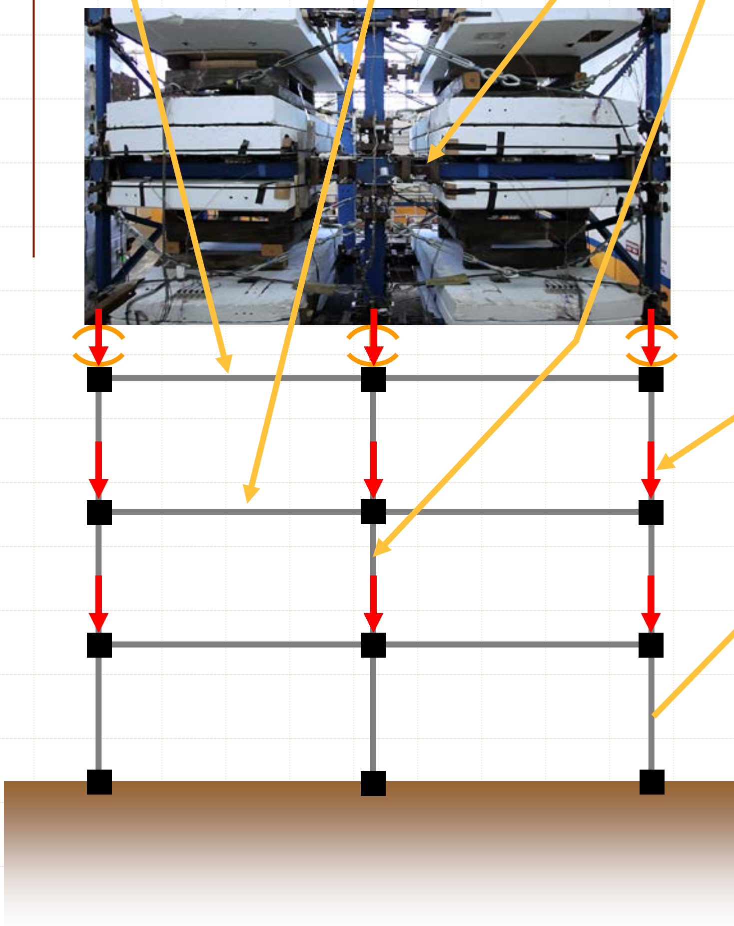
- Inertia
- Energy Dissipation
- Resistance

Hybrid Shake Table

$$\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}+\mathbf{P_r}\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right)=\mathbf{P}\left(t\right)$$

Dynamic Loading:
- Seismic
- Wind
- Blast/Impact
- Wave
- Traffic

Static Loading:
- Gravity
- Prestress



analytically add nonlinear geometric effects to measured resisting forces

analytical model of structural energy dissipation and inertia

physical model of structural resistance

Equations of Motion

1. Slow test

$$\mathbf{M}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

2. Rapid test

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} - \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}^{E} - \mathbf{C}^{E}\dot{\mathbf{U}}_{i+1}^{E}$$

3. Real-time test

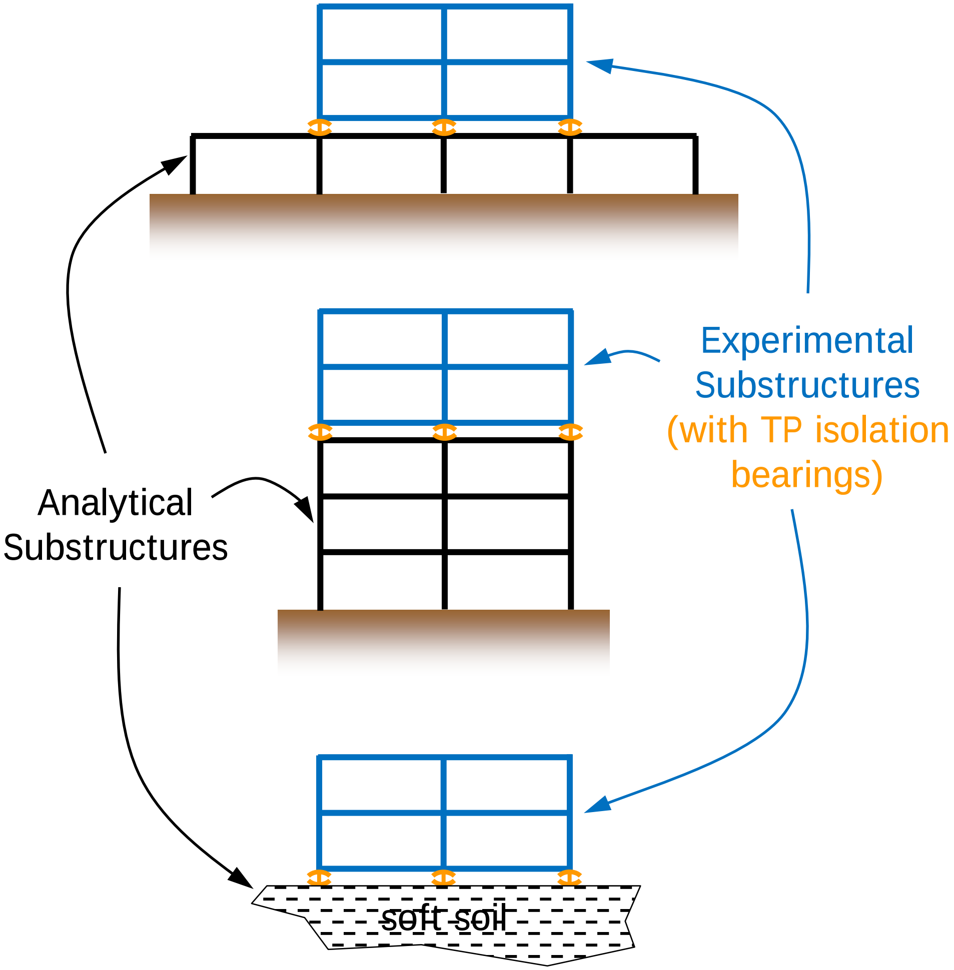
$$\mathbf{M}^{A}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}^{A}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

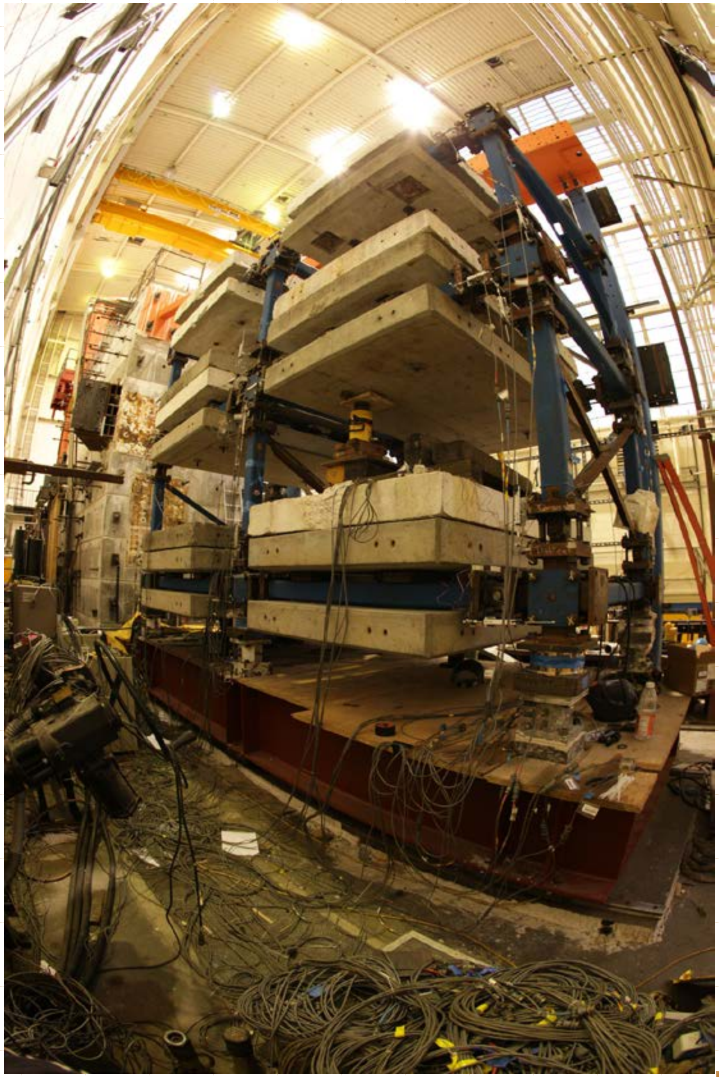
$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}$$

4. Smart shaking table test

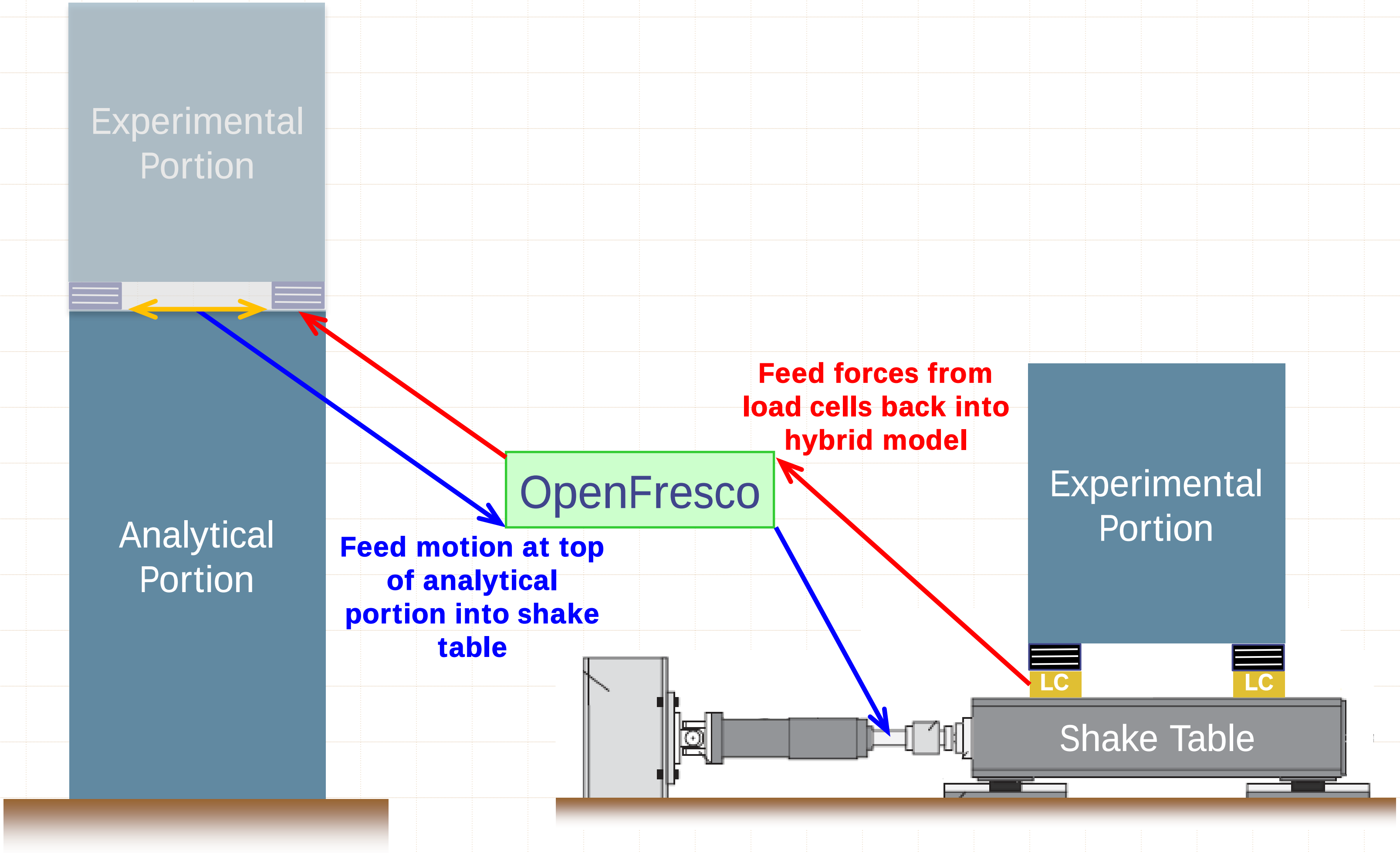
$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{\mathbf{t},i+1}, \dot{\mathbf{U}}_{\mathbf{t},i+1}, \ddot{\mathbf{U}}_{\mathbf{t},i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{\mathbf{t},\,i+1}$$

Hybrid Shake Table Test

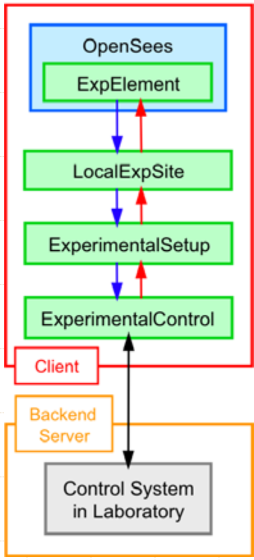




Hybrid Shake Table Configuration



Connecting to MTS 493 controller



OpenSees Finite Element Model

OpenFresco Middleware

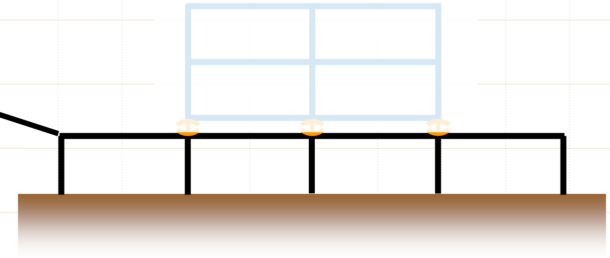
SCRAMNet

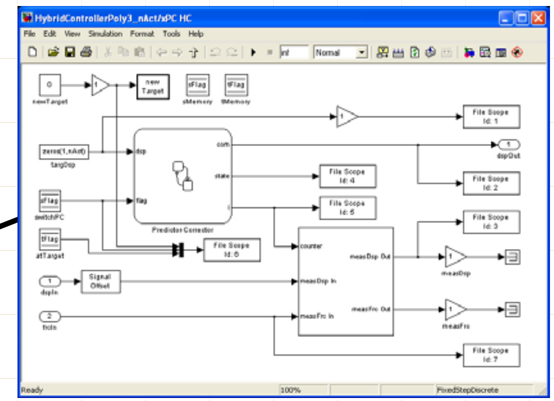
xPC-Target real-time Predictor-Corrector

SCRAMNet

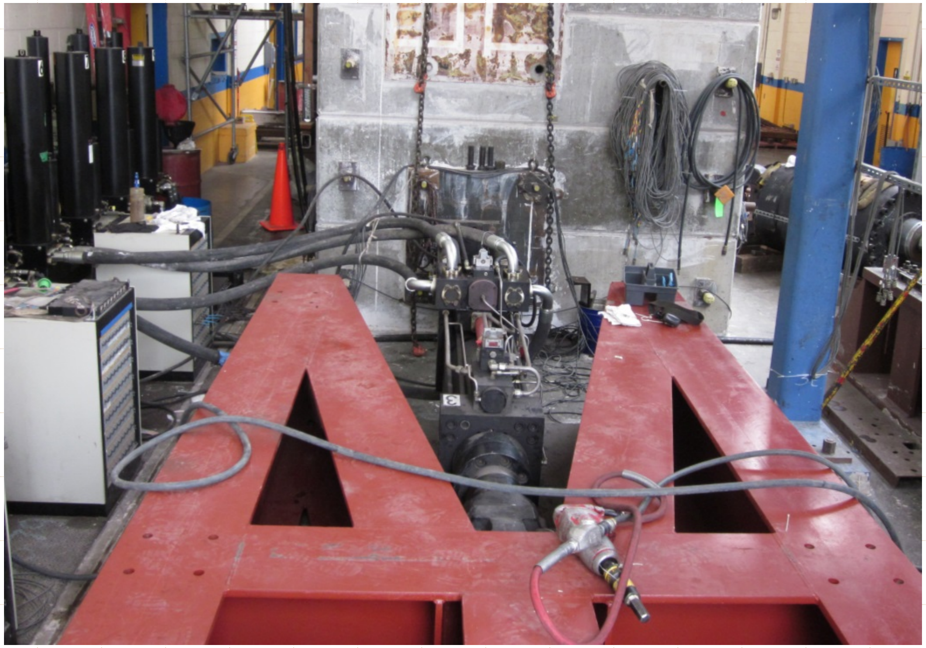
MTS 493 real-time Controller

Physical Specimen in NEES Lab



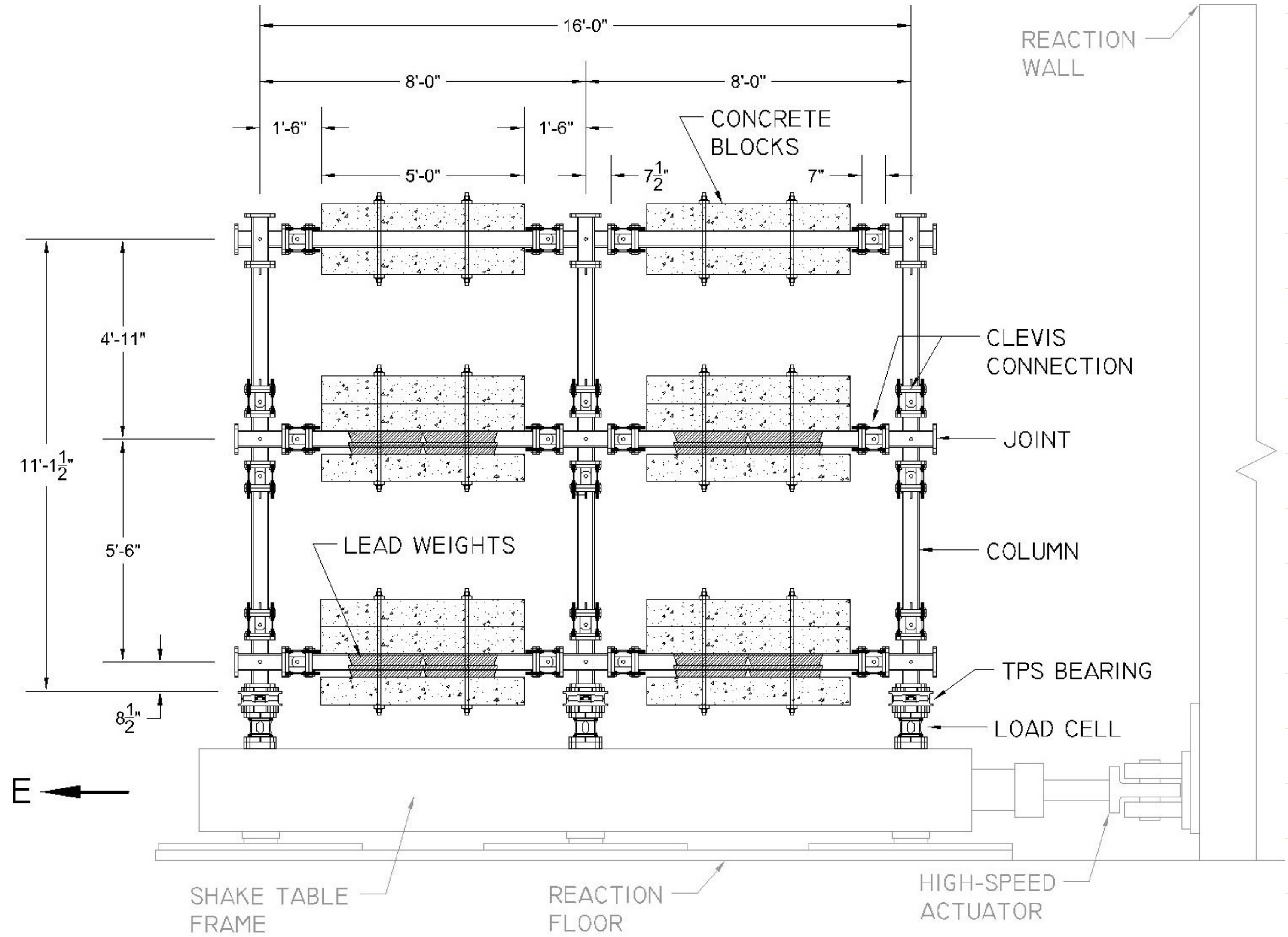


Shake Table

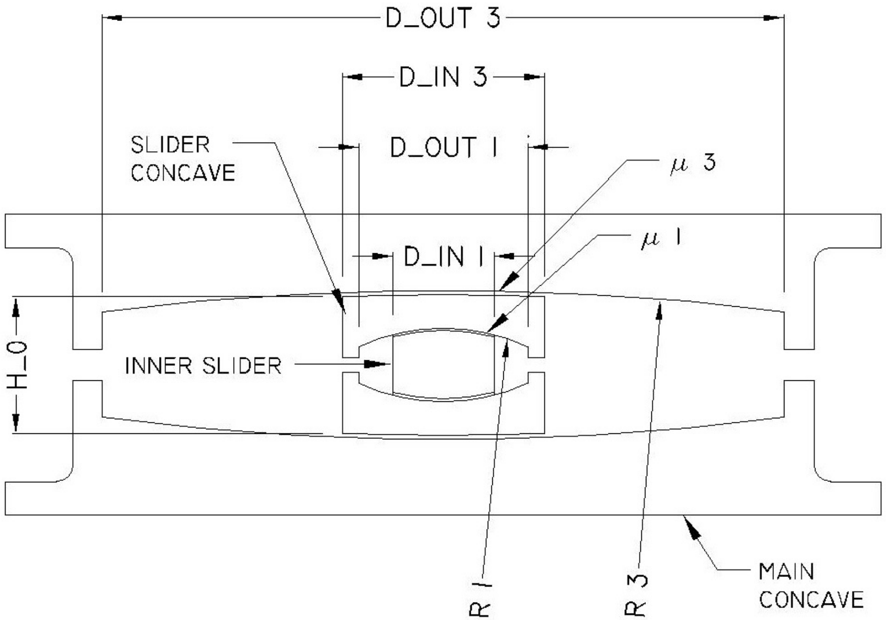


- 5.8m x 2.1m platform
- Linear bearings with μ < 10%
- Actuator with 1000kN, $\pm$0.5m and $\pm$1m/sec capacity

Specimen


16'-0"
8'-0"
8'-0"
1'-6"
1'-6"
5'-0"
7 1/2"
7"
CONCRETE BLOCKS
REACTION WALL
CLEVIS CONNECTION
JOINT
COLUMN
LEAD WEIGHTS
TPS BEARING
LOAD CELL
4'-11"
11'-1 1/2"
5'-6"
8 1/2"
E
SHAKE TABLE FRAME
REACTION FLOOR
HIGH-SPEED ACTUATOR

Triple Friction Pendulum Bearings



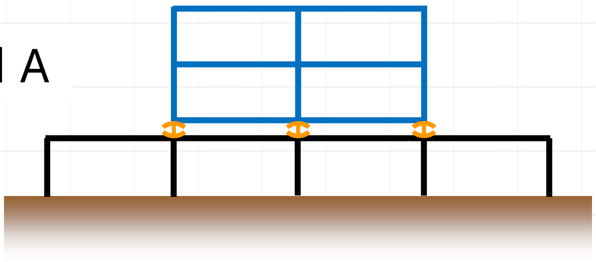
T_{eff} = 1.4 sec @ 10cm

PROPERTY	VALUE
R 1	3.00"
R 3	18.64"
D_IN 1	1.5"
D_IN 3	3.0"
D_OUT 1	2.5"
D_OUT 3	9.0"
H_0	6.0"
μ 1	2%
μ 3	9%

1/3rd scale

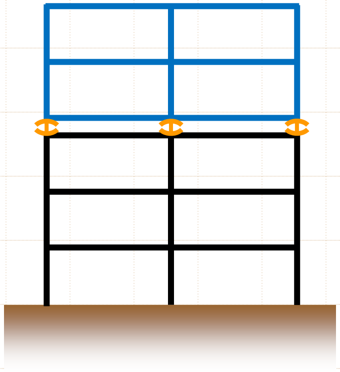
Analytical Substructure Parameters

Model A



W_{floor} (kN)	T_1	ζ_1
445	1.01	0.03
445	0.51	0.03
445	0.25	0.03
445	0.13	0.03

Model B



W_{floor} (kN)	T_1	T_2	T_3	$\zeta_{1,3}$
142	1.02	0.36	0.25	0.03
142	0.51	0.18	0.13	0.03
142	0.25	0.09	0.06	0.03

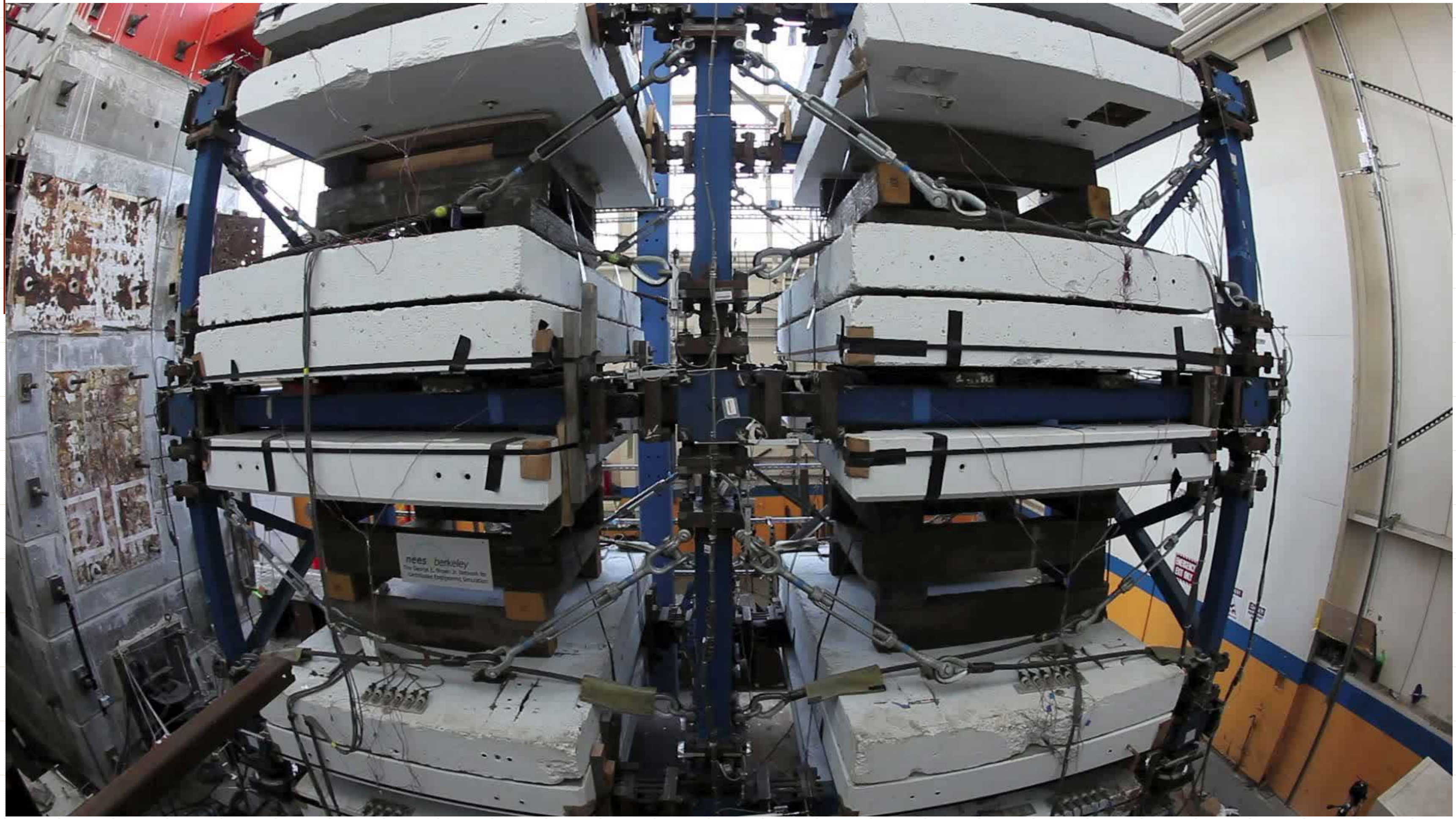
Important Analysis Parameters

- OpenSees as computational driver
- Using Newmark Explicit ($\beta = 0$, $\gamma = 0.5$)
- No iterations necessary
- But conditionally stable
  - $dt < T_{min}/\pi = 0.06/\pi = 0.01997$ sec
  - choose $dt_{int} = dt_{sim} = 5/1024 = 0.00488$ sec
- Using MultipleSupport excitation pattern in OpenSees to get absolute response
- SCRAMNet experimental control is used to reduce communication delays

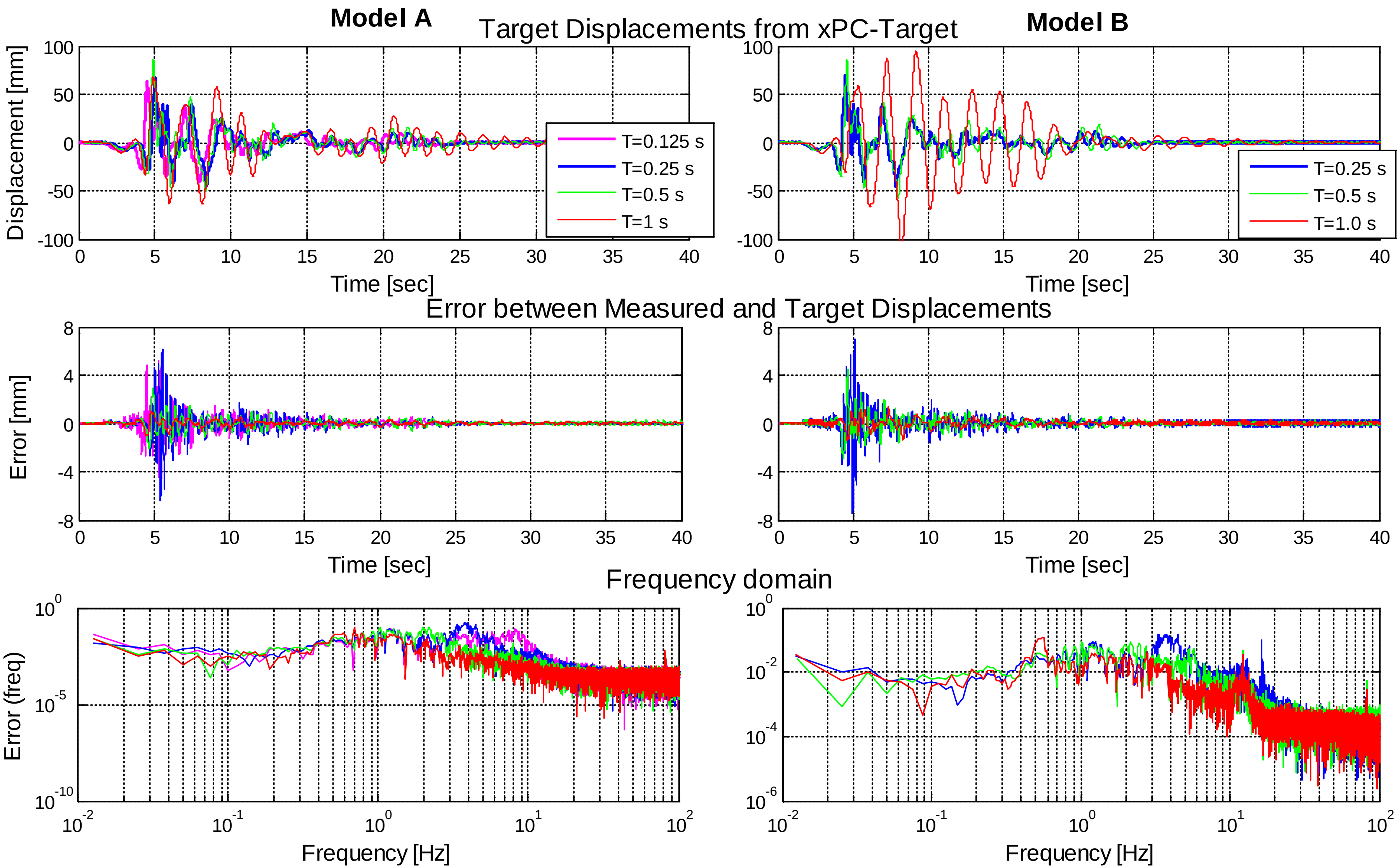
Ground Motion

- Loma Prieta Gilroy #4 Array
  - DBE 10% chance of exceedance in 50 years
- Scaled so expected bearing displ. was just within the maximum displ. of the bearings (18 cm) under the MCE level, or 2% chance of exceedance in 50 years

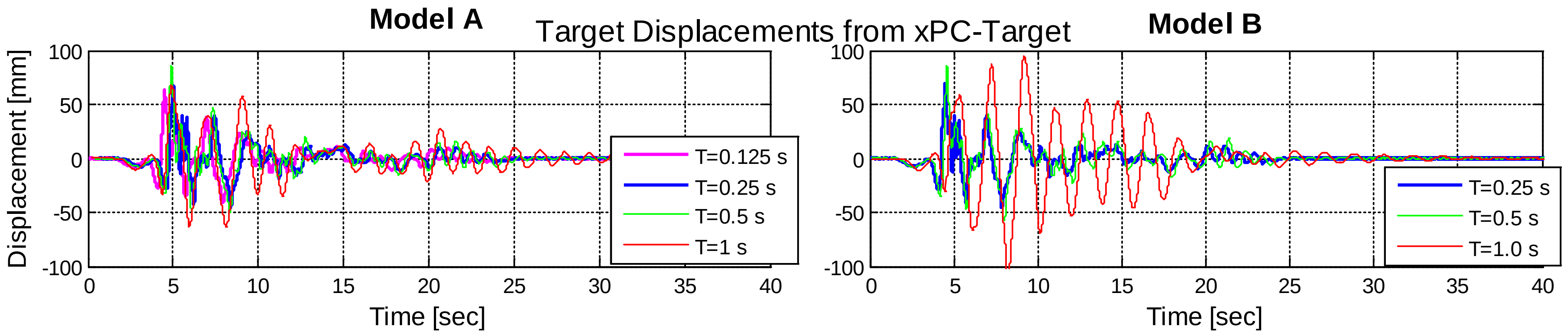
Movie of Test

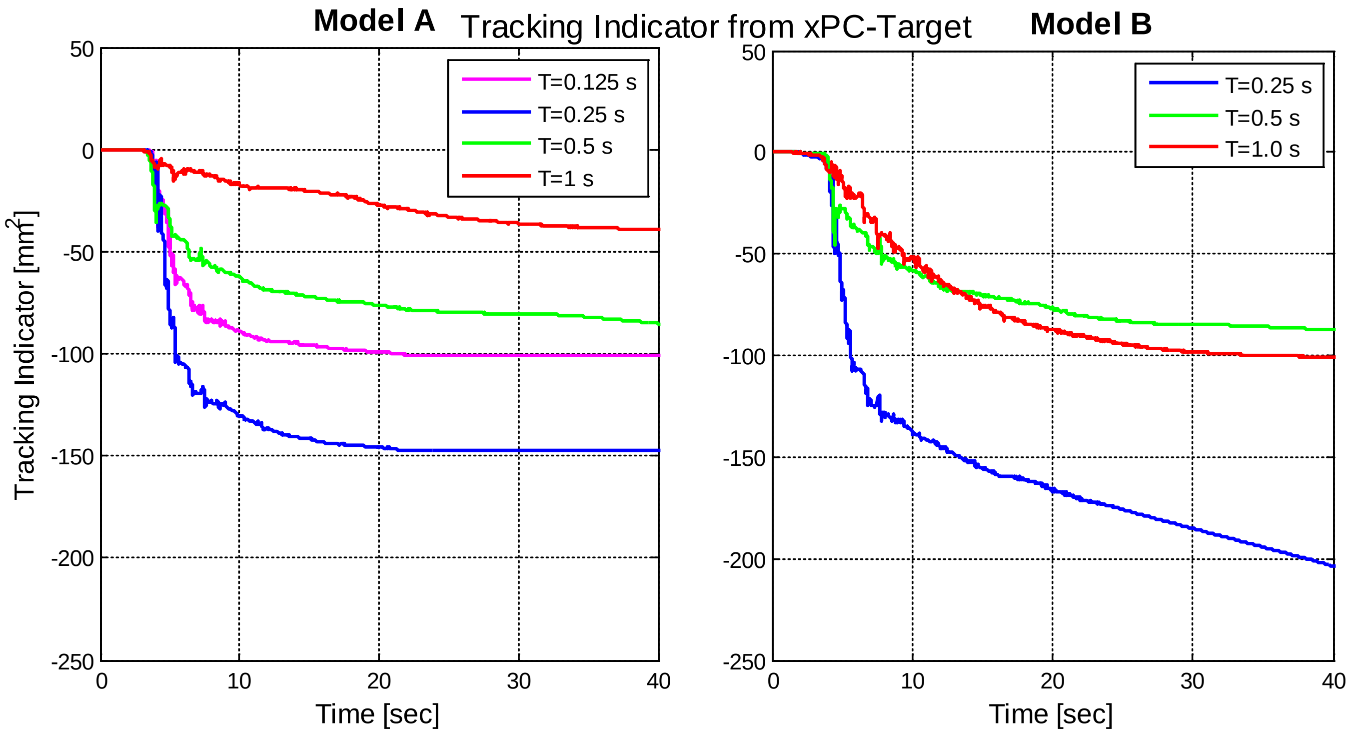


Shake Table Displacements

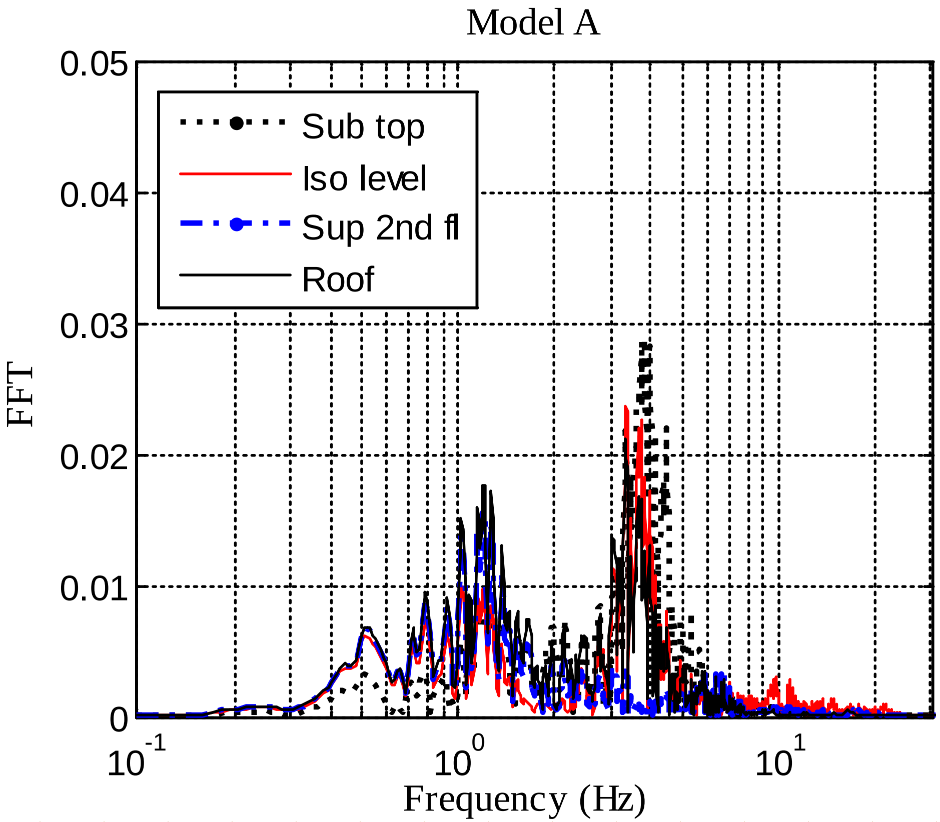


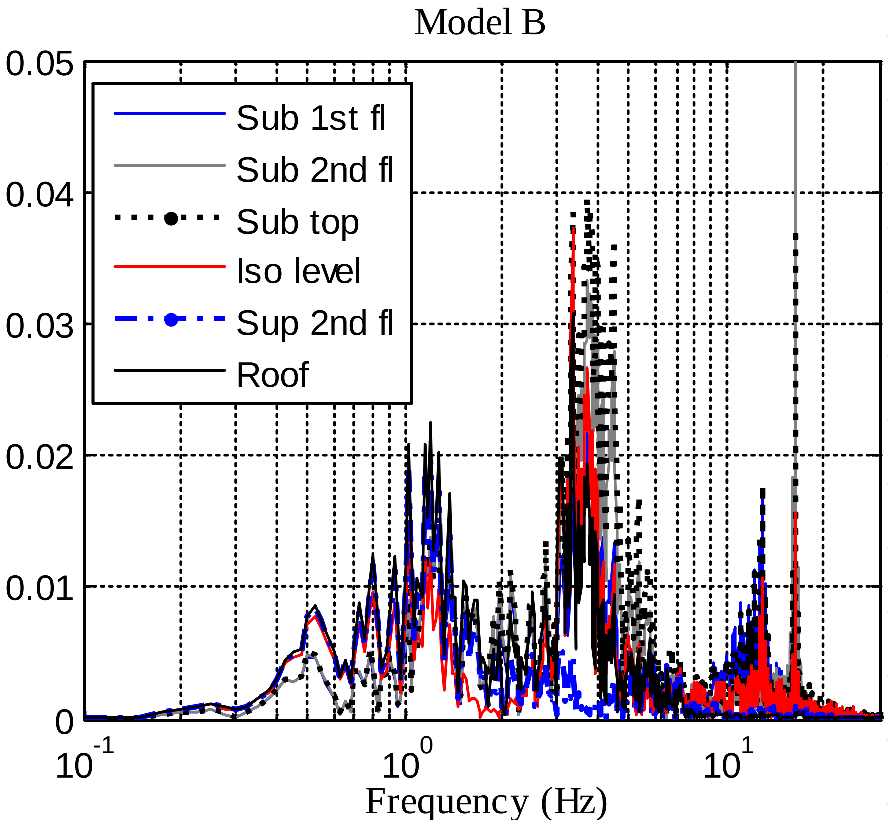
Tracking Indicators



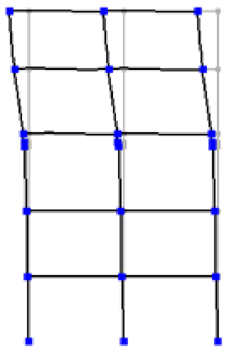
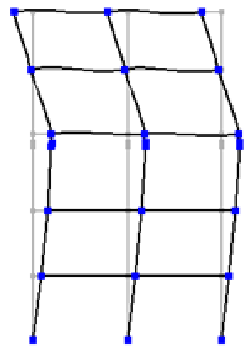
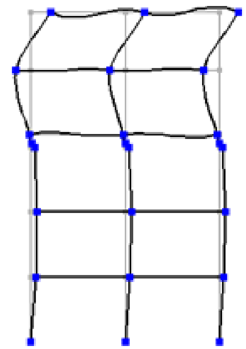
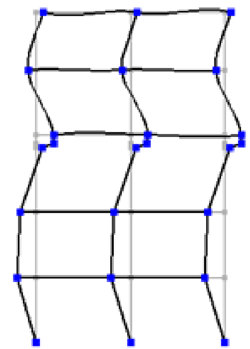
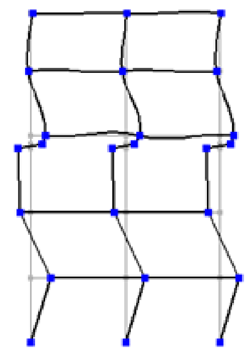
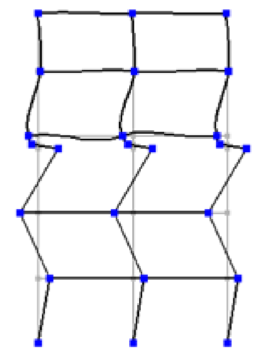
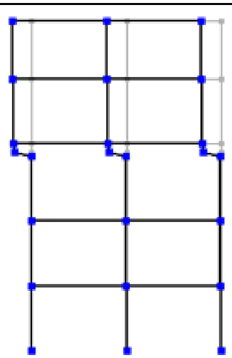
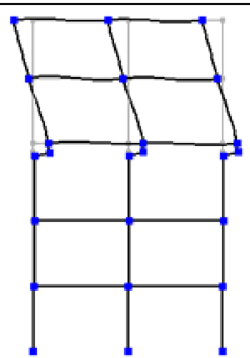
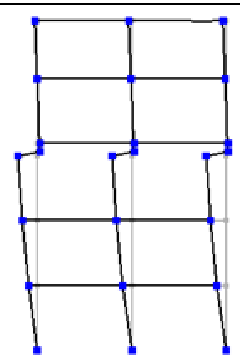
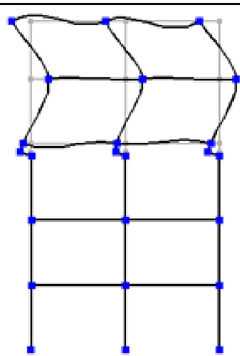
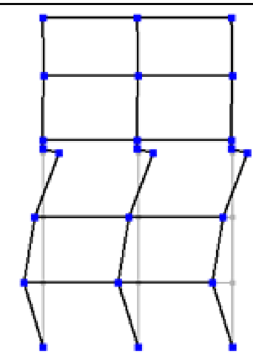
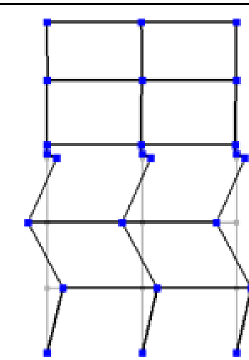


FFTs of acc. histories for T = 0.25 sec

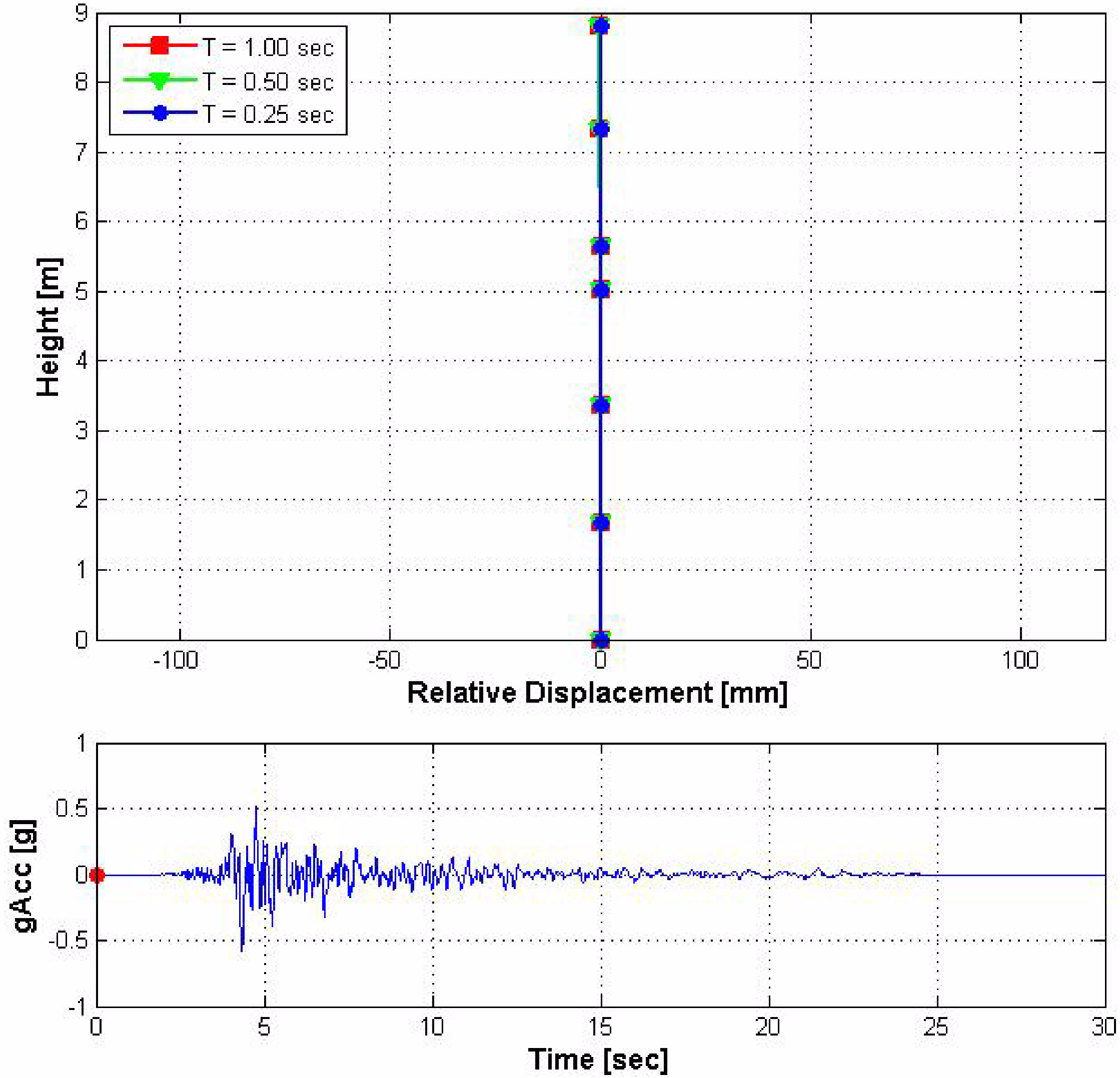




Mode shapes and frequencies

Mode	1	2	3	4	5	6
k_{iso} = initial	 1.7 Hz	 3.6 Hz	 7.0 Hz	 9.6 Hz	 14.2 Hz	 17 Hz
k_{iso} = 2nd sliding stage	 0.51 Hz	 3.4 Hz	 4.0 Hz	 7.6 Hz	 11.0 Hz	 15.9 Hz

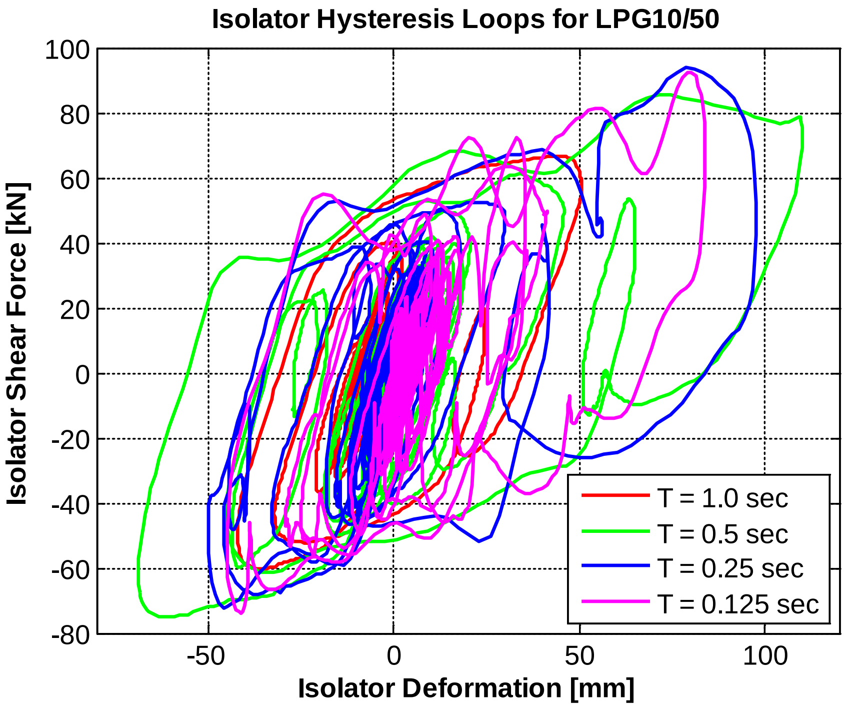
Relative Displacement Model B

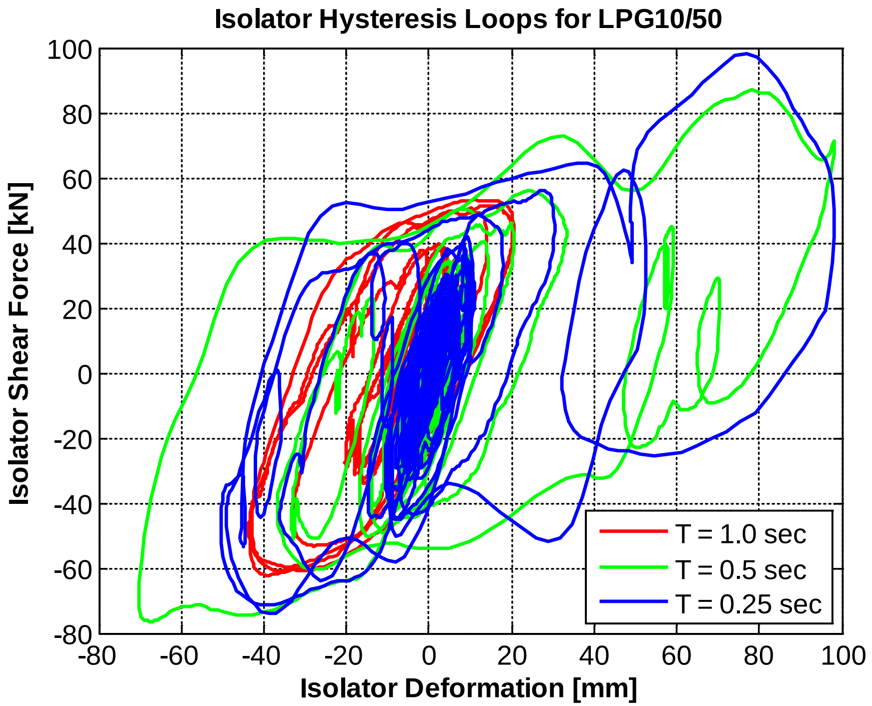


Isolator Hysteresis Loops

Model A

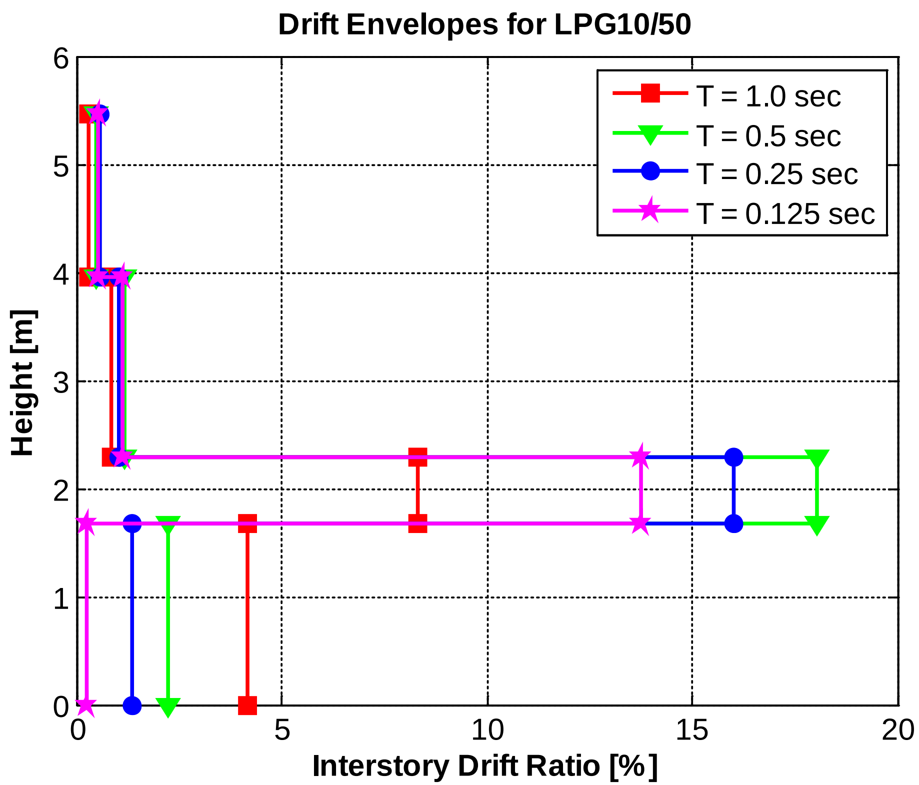
Model B



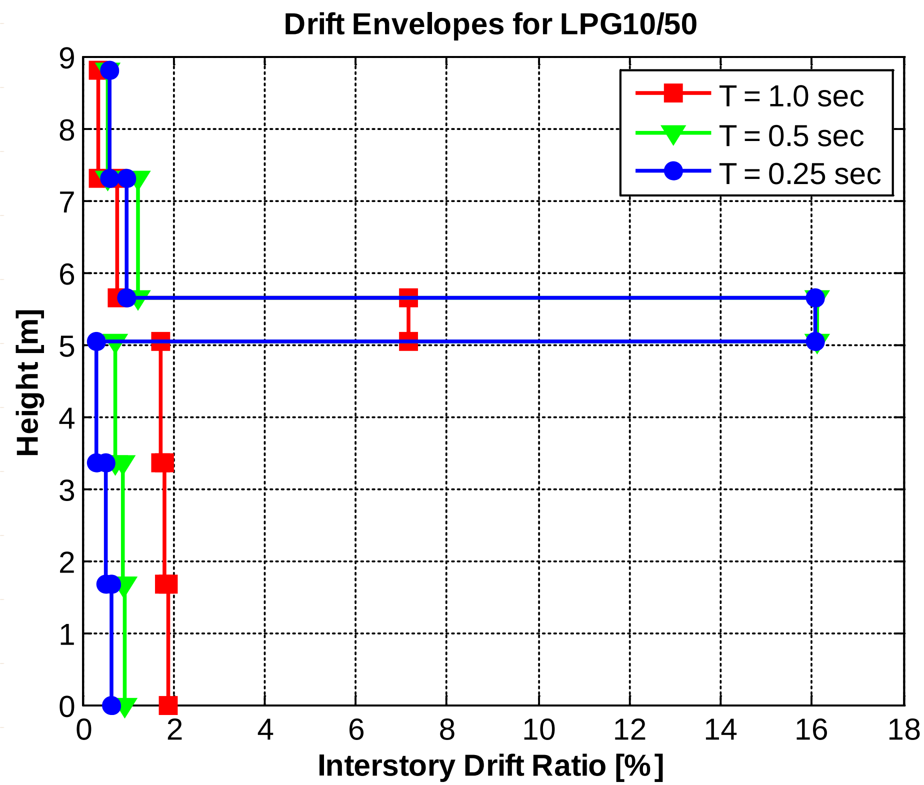


Drift Envelopes

Model A



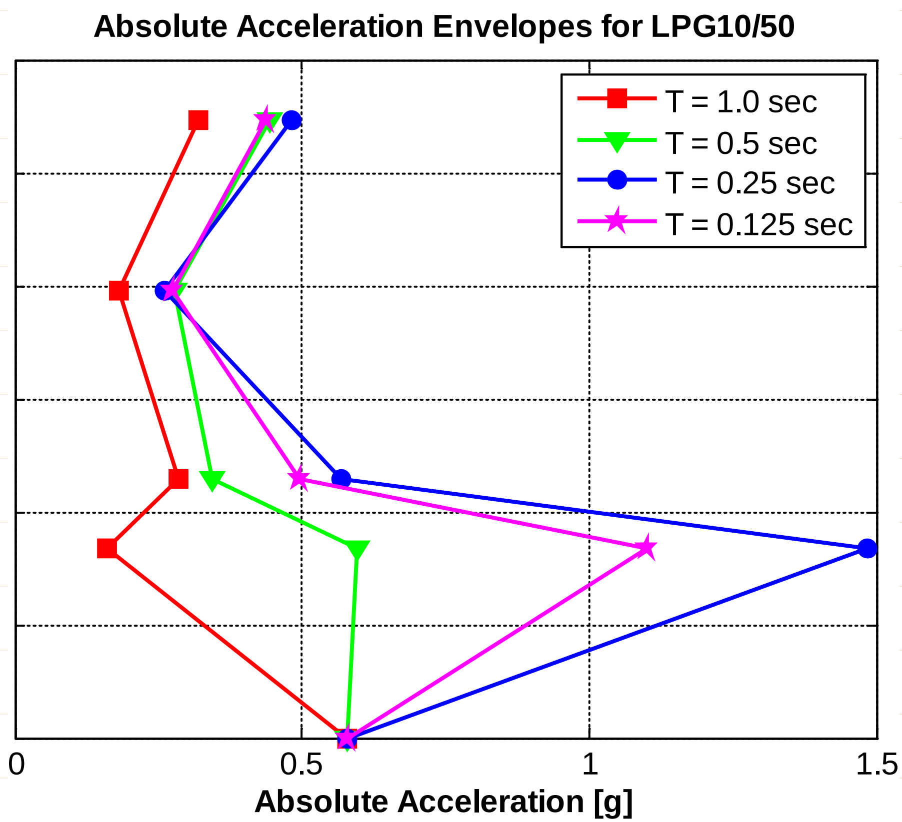
Model B

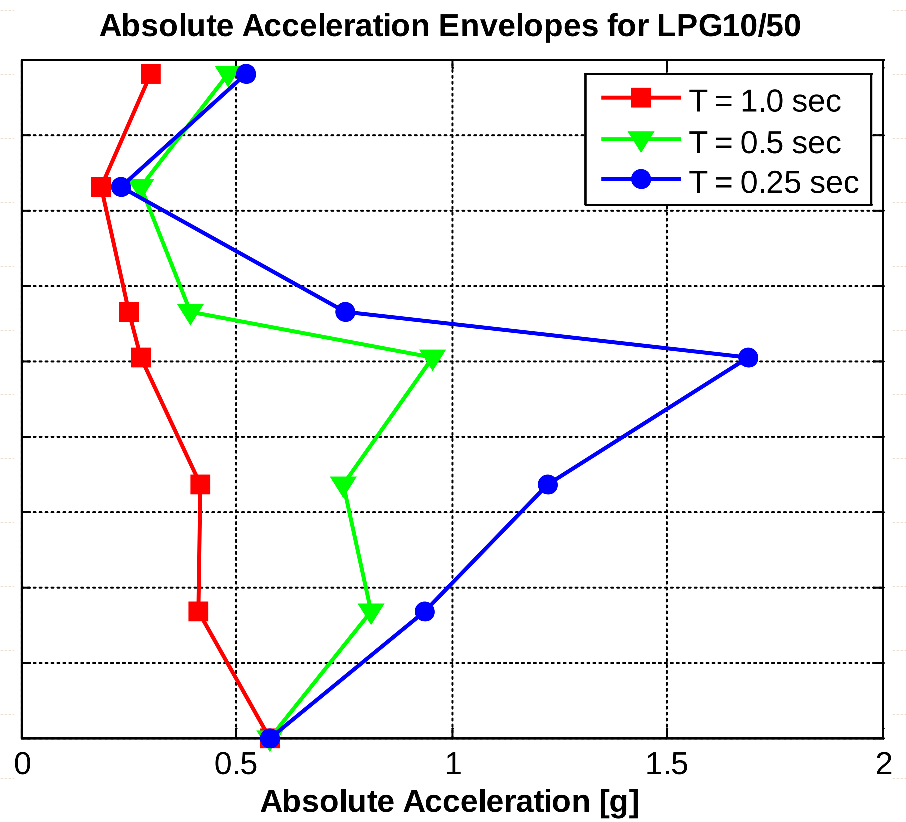


Response Envelopes

Model A

Model B

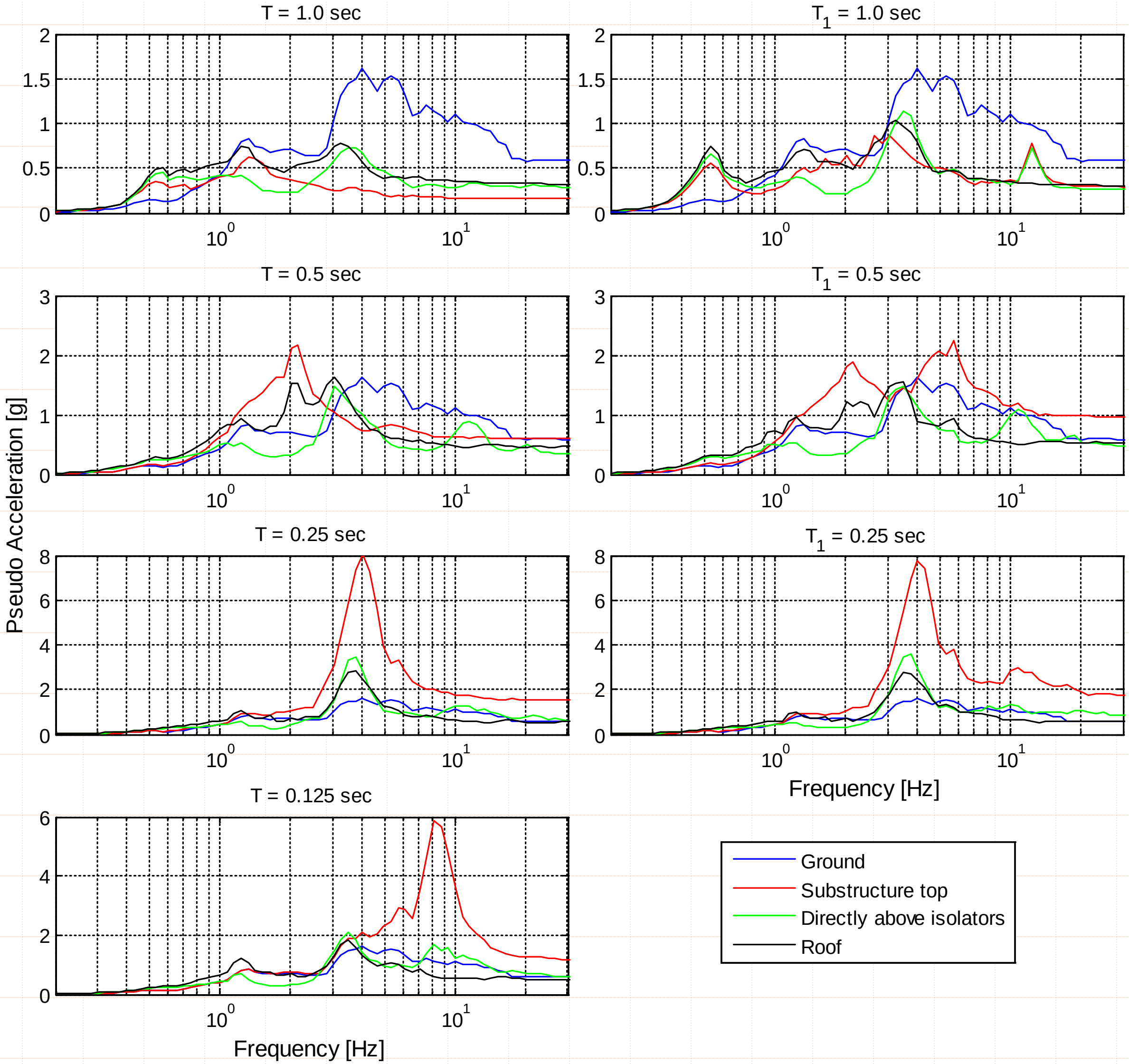




Floor Response Spectra

Model A

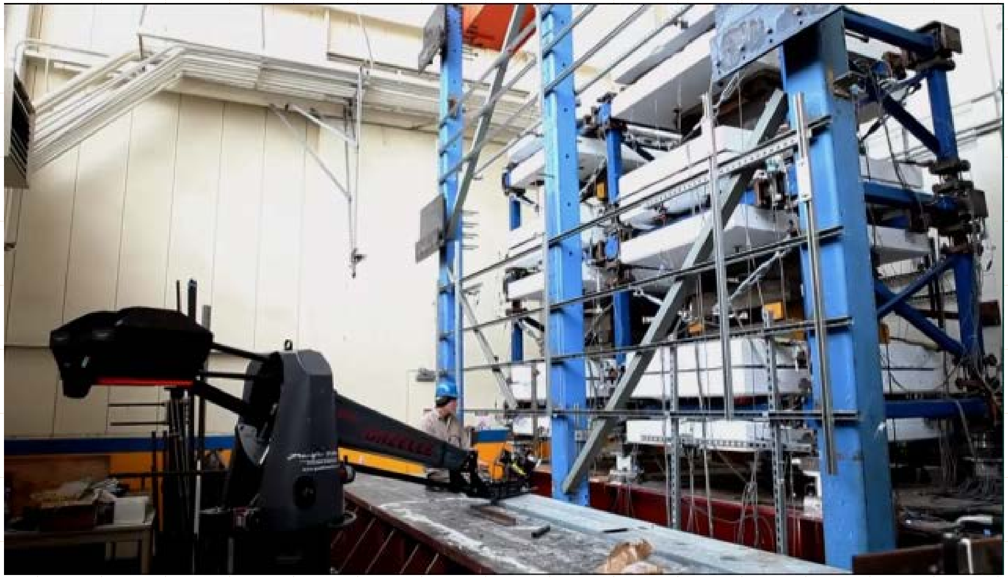
Model B

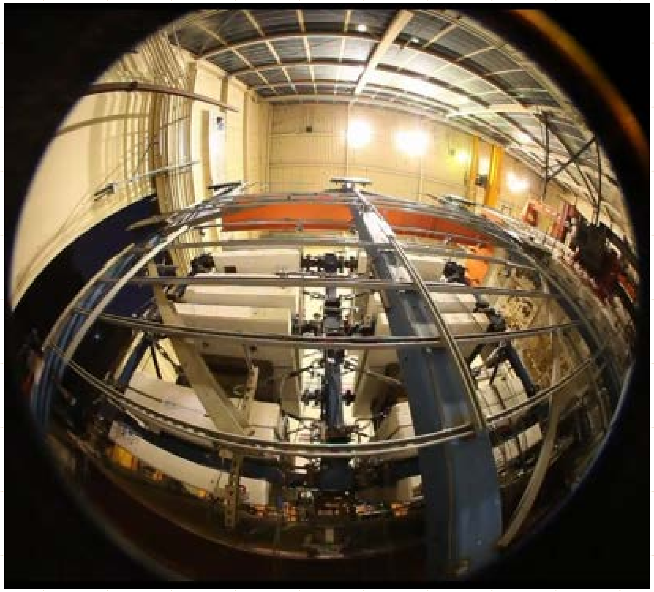


Conclusions

- Efficiently tested portion of the structure using novel real-time hybrid shake table
- Hybrid testing reproduced desired input
- Isolation displacement was larger for short period substructures
- The level of superstructure response is tied only to the peak acceleration levels coming from the substructure, with larger accelerations resulting in larger superstructure responses

Earthquake Exhibit: Life on a Dynamic Planet





CALIFORNIA ACADEMY OF SCIENCES

EARTH QUAKE

Tongji University Project with MTS

Example 2: Seismic Isolation of NPP

Outline for Example 2

1. Motivation
2. SRMD Testing Facility
3. Isolator Test Specimens
4. Hybrid Models of NPPs
5. OpenSees and OpenFresco Details
6. Preliminary Results
7. Failure Tests
8. Summary & Conclusions

Motivation

HS of large isolated structure

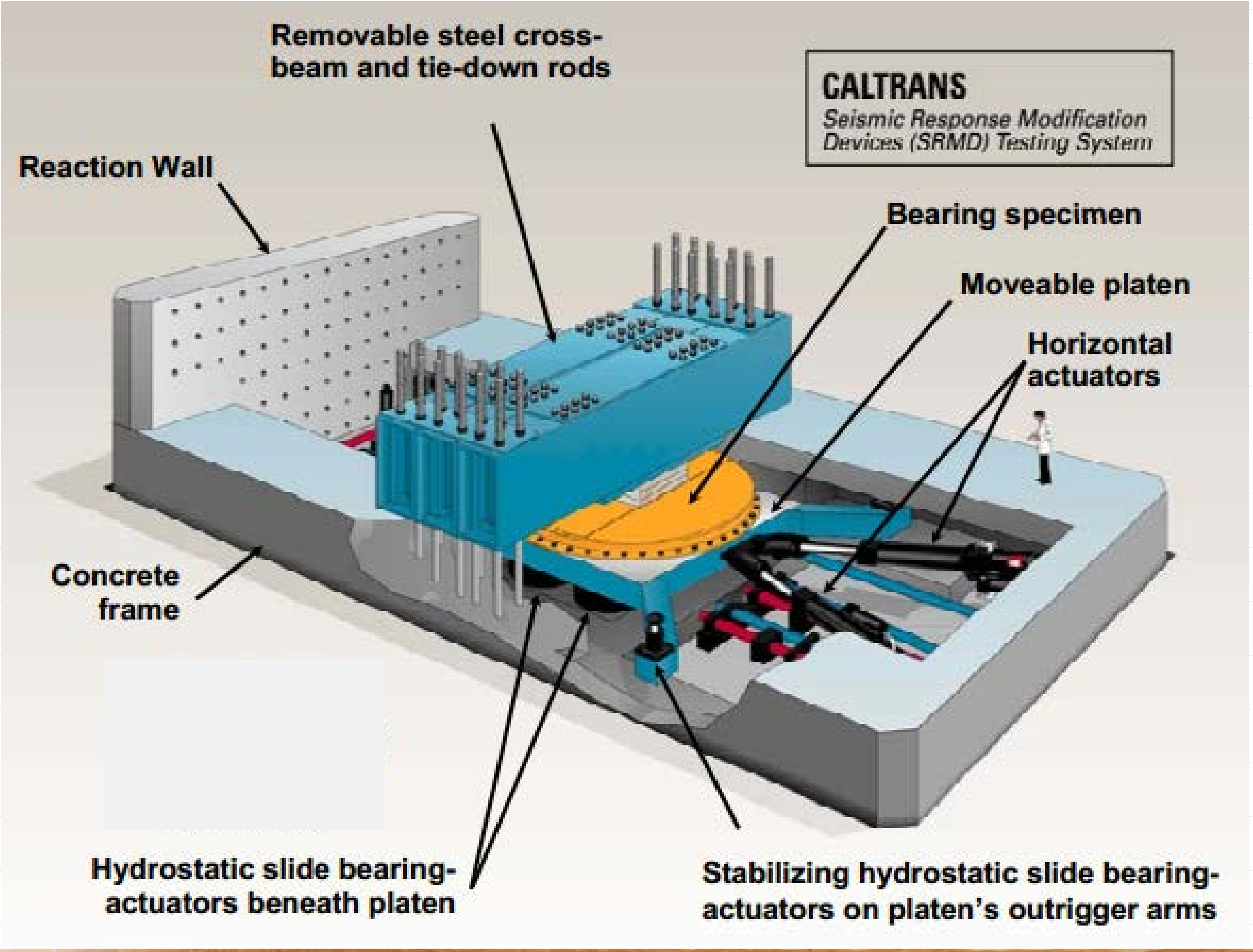
- On a shaking table the testing of large structures such as NPPs is impractical due to the size, weight and strength limitations imposed by the simulator platform
- Using hybrid simulation
  - The linear-elastic plant superstructure can be modelled analytically
  - Only the nonlinear isolator behavior needs to be tested physically
  - Large axial loads due to gravity and axial load fluctuations due to overturning and vertical input can be imposed in force control

HS of large isolated structure

- Using hybrid simulation
  - No complex active or passive gravity load setups are necessary
  - Actuator movements will limit displacements during limit state tests
  - Hence, when testing limit states, such as moat wall impact, bearing rupture or uplift, there is no need to protect expensive test equipment from specimen impact
- Need a testing facility that can be converted to perform hybrid simulations on large full-scale isolators

SRMD Testing Facility

Overview of SRMD @ UC San Diego

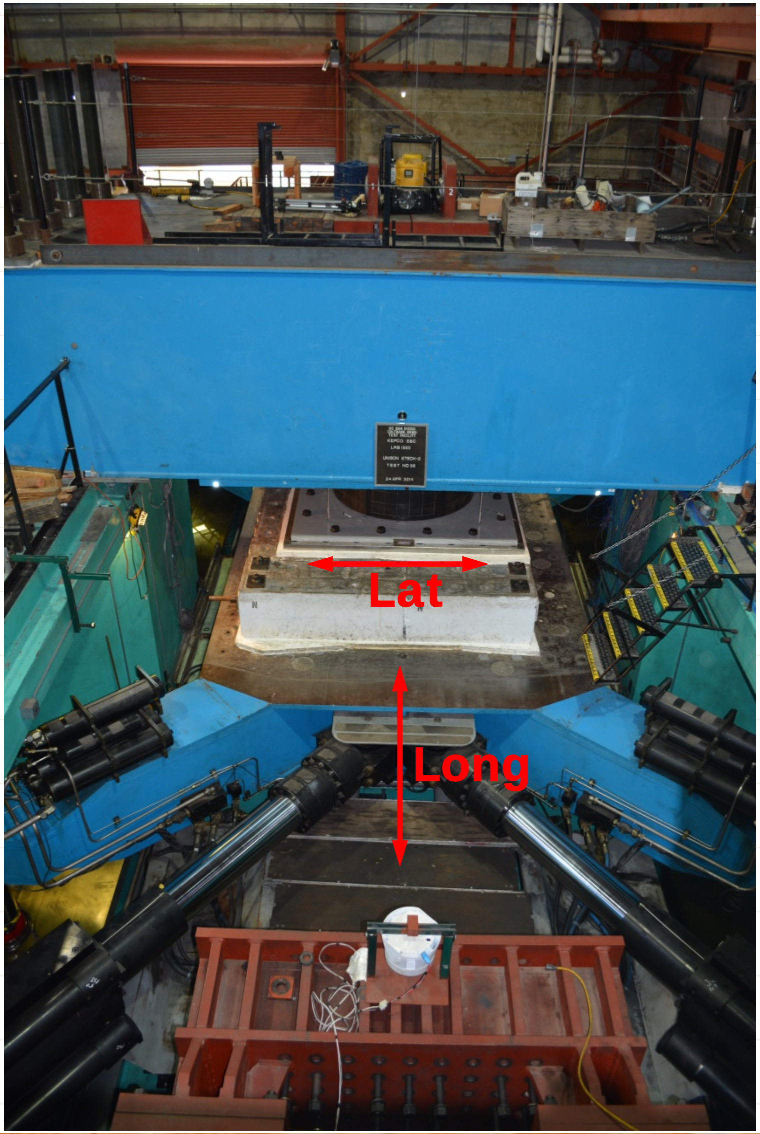


Overview of SRMD @ UC San Diego

Specifications of SRMD testing facility

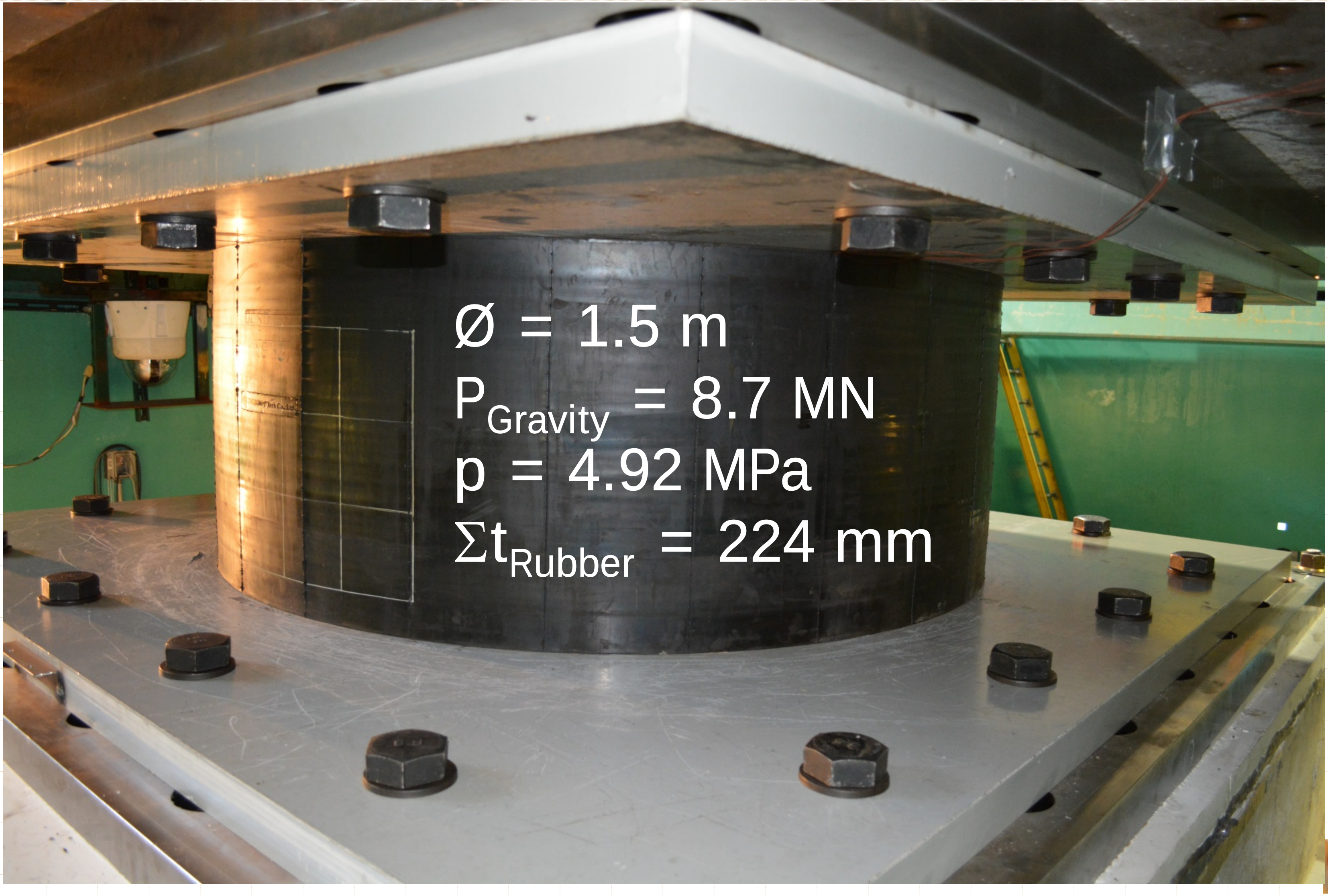
Component	Capacity	
Vertical Force	53,400 kN	12,000 kips
Longitudinal Force	8,900 kN	2,000 kips
Lateral Force	4,450 kN	1,000 kips
Vertical Displacement	± 0.127 m	± 5 in
Longitudinal Displacement	± 1.219 m	± 48 in
Lateral Displacement	± 0.610 m	± 24 in
Vertical Velocity	± 254 mm/s	± 10 in/s
Longitudinal Velocity	± 1,800 mm/s	± 70 in/s
Lateral Velocity	± 760mm/s	± 30 in/s
Relative Platen Rotation (Roll, Pitch, & Yaw)	± 2 degrees	
Maximum Specimen Height	1.524 m	60 in

Built in 1999 by Caltrans, UCSD and MTS

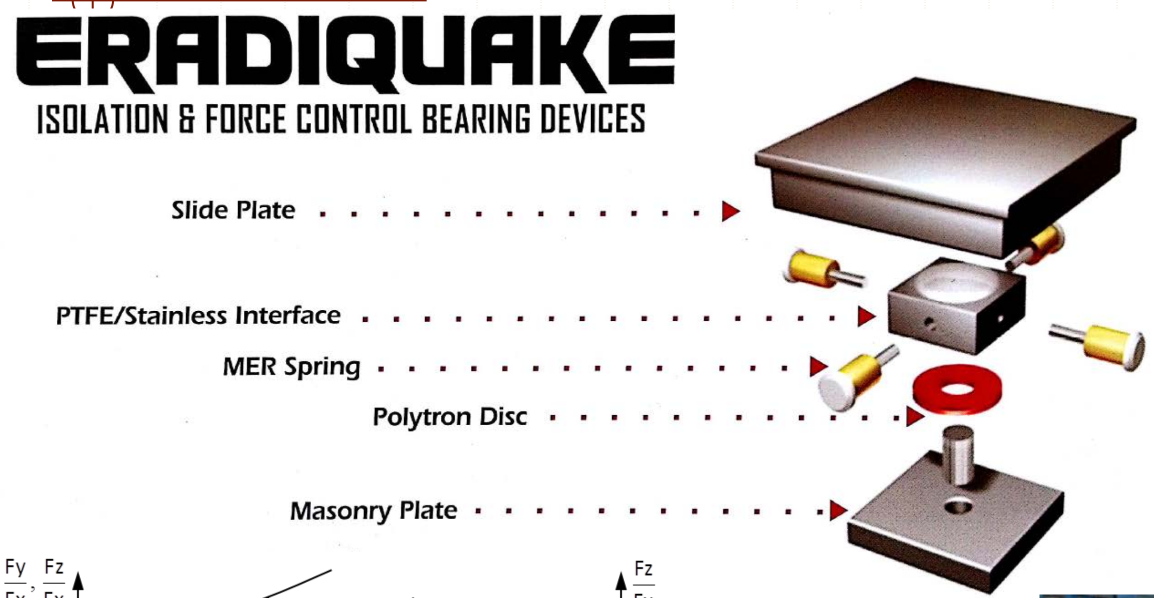


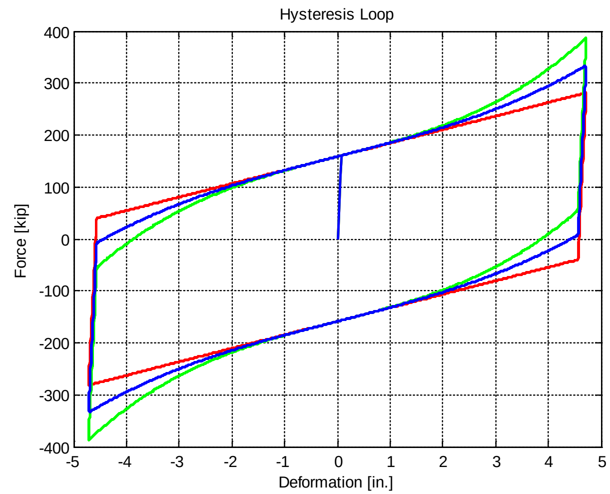
Isolator Test Specimens

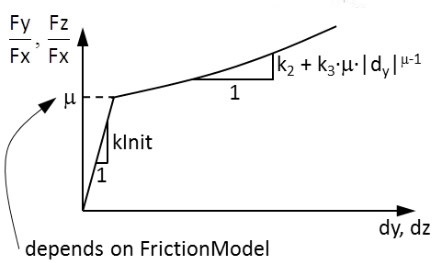
LPRB Isolator by Unison

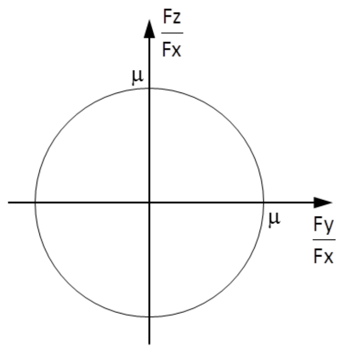


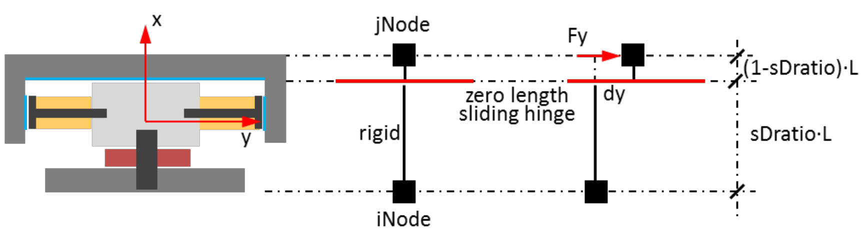
EQSB Isolator by ESCO RTS





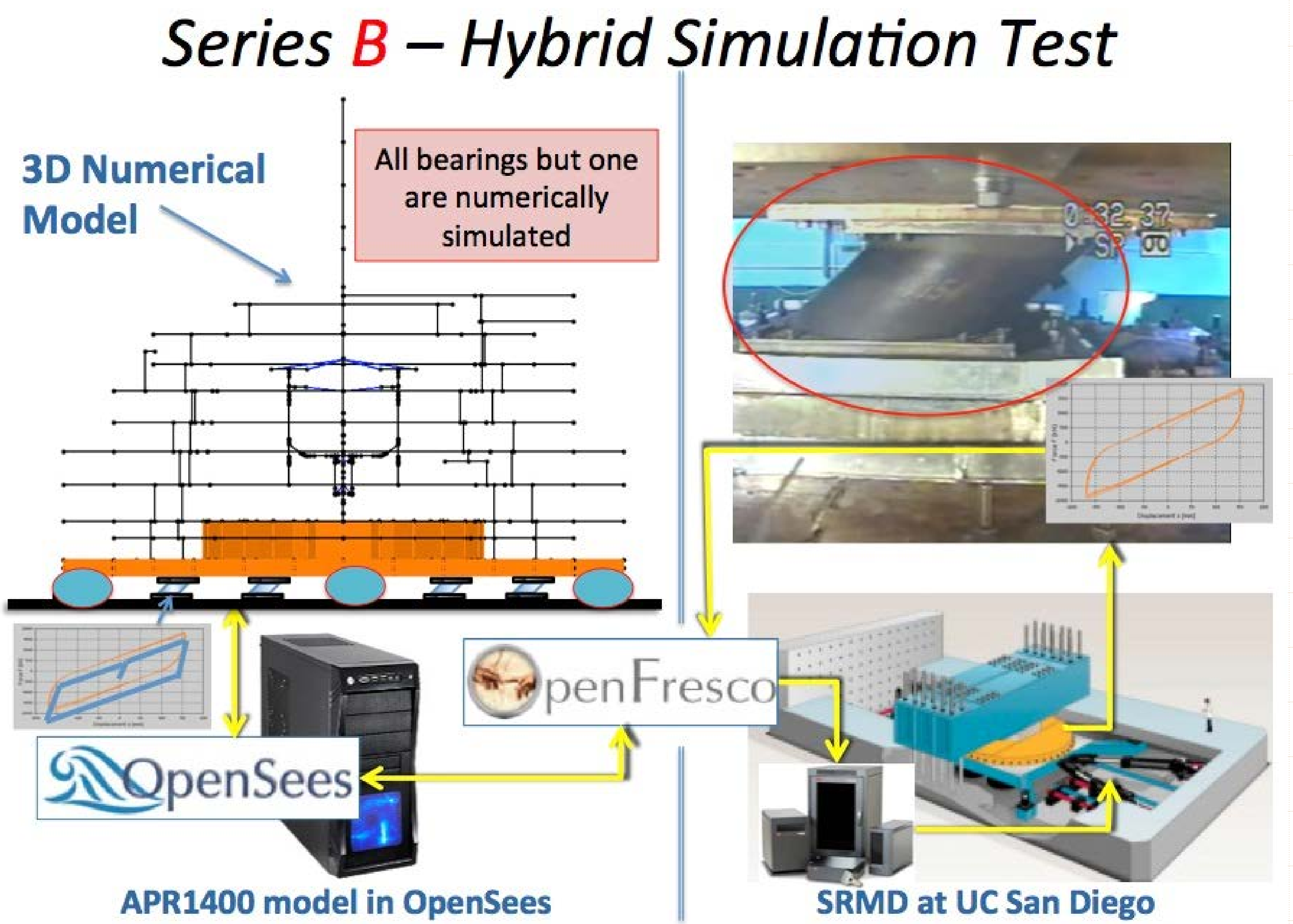




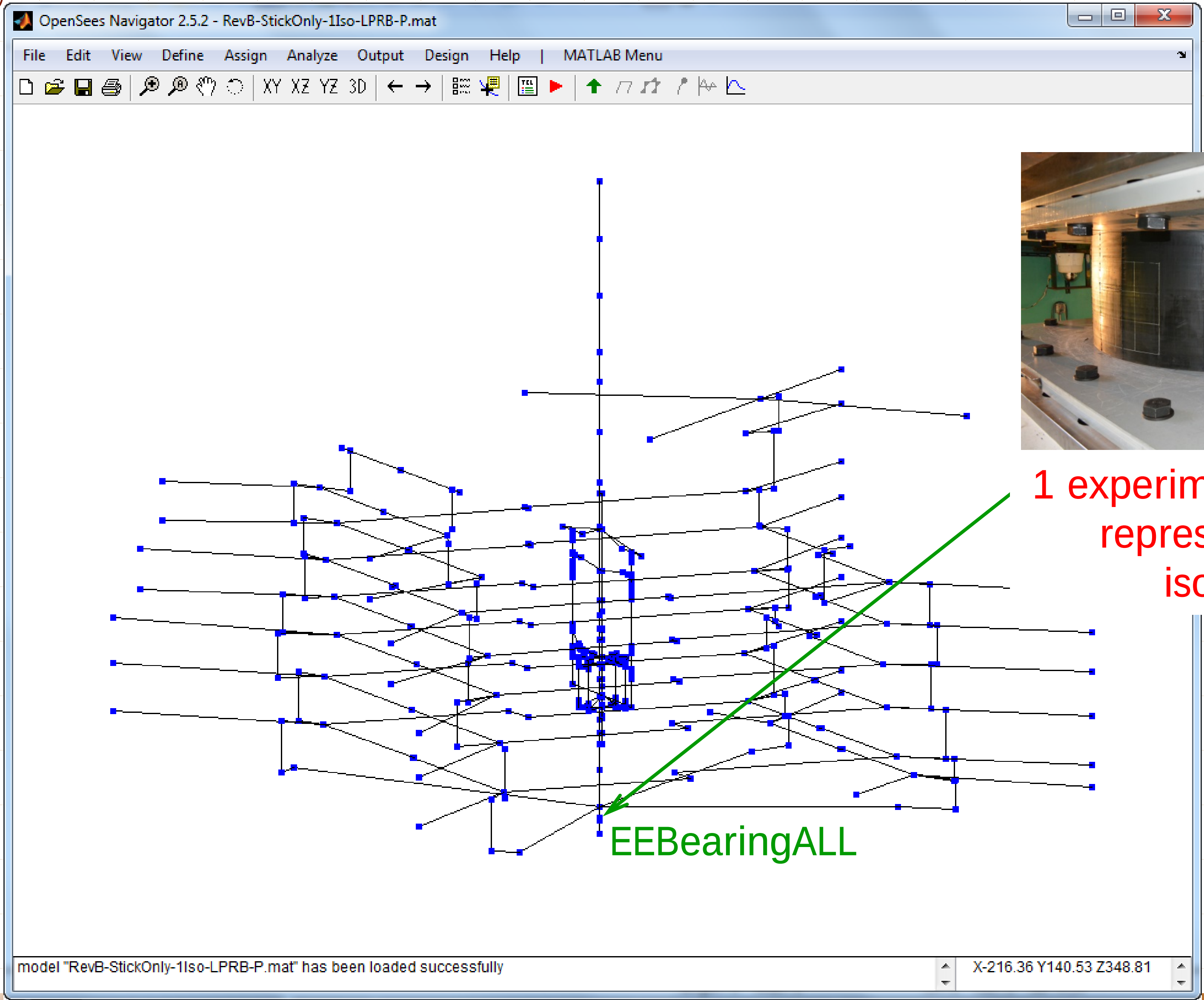


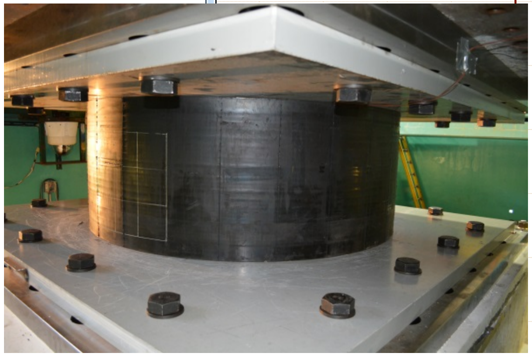
Hybrid Models

Hybrid Models



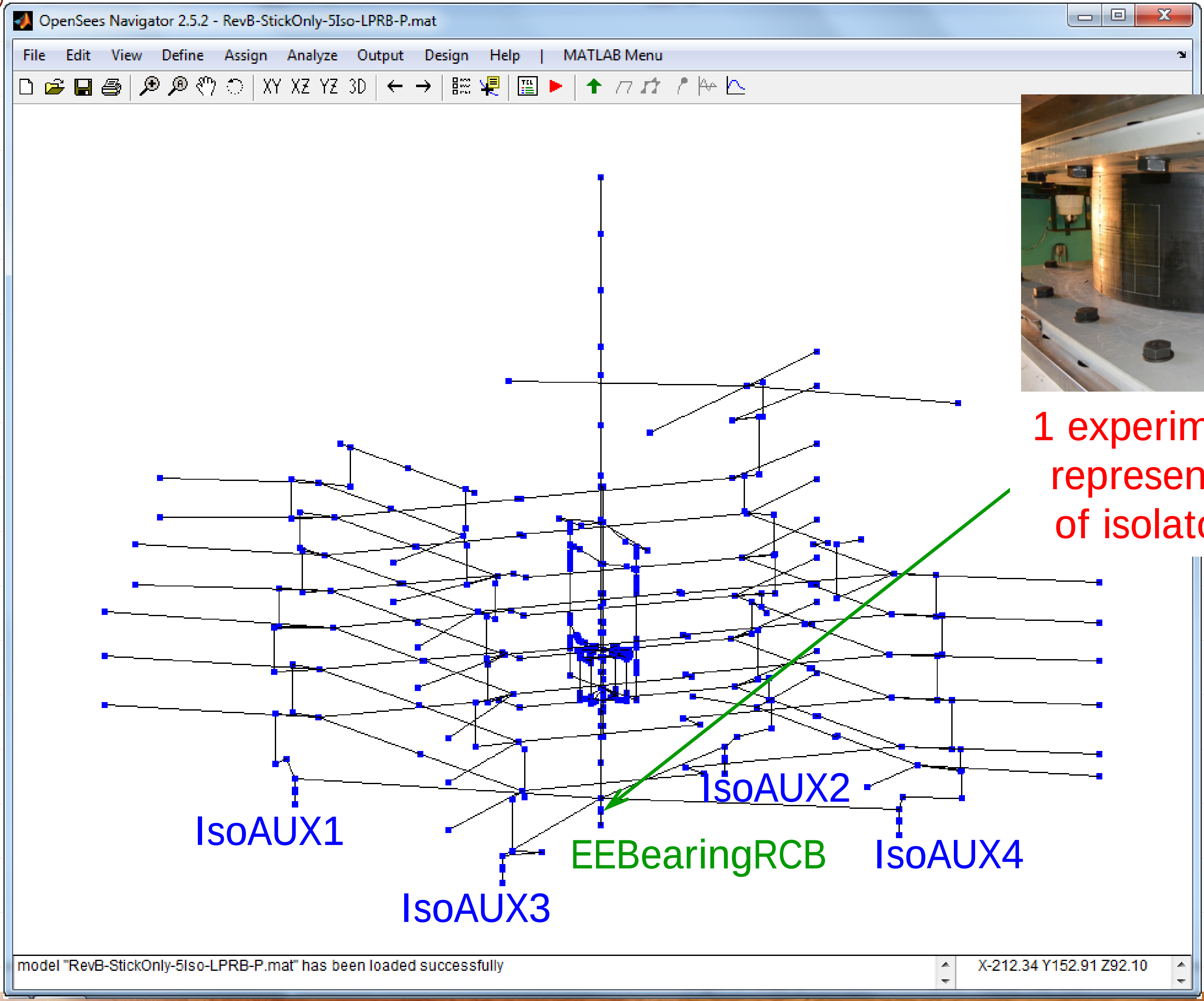
A) Model with 1 isolator

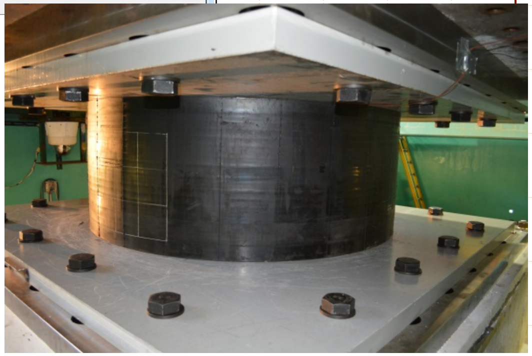




1 experimental isolator representing all isolators

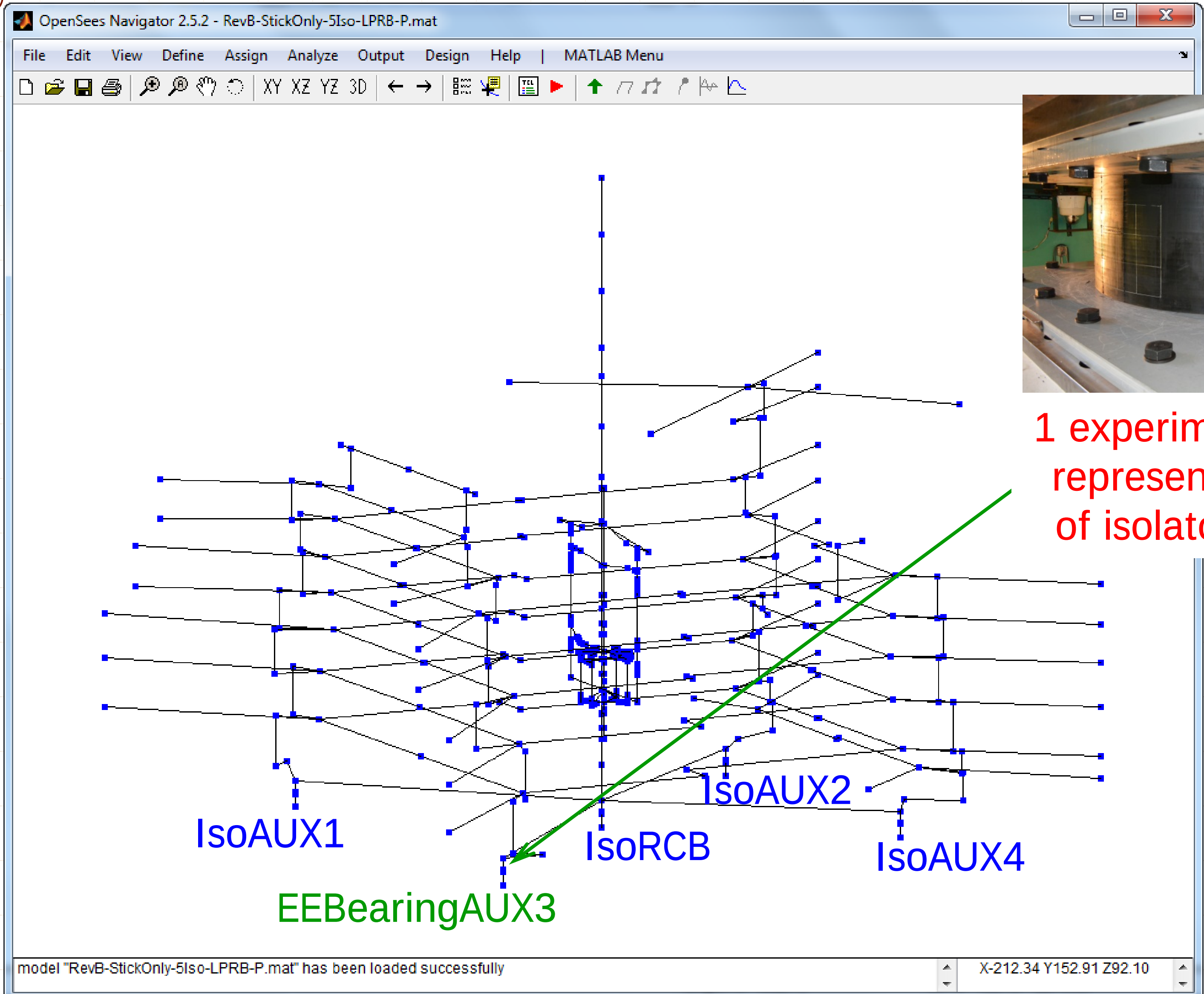
B) Model with 5 isolators (center)

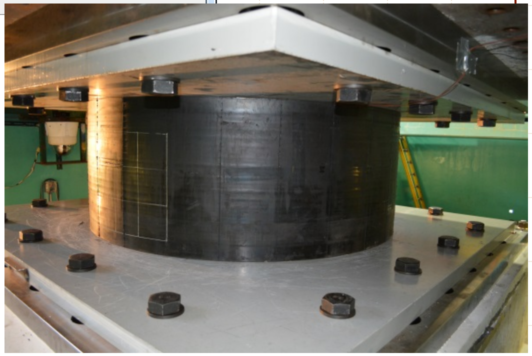




1 experimental isolator representing a group of isolators in center

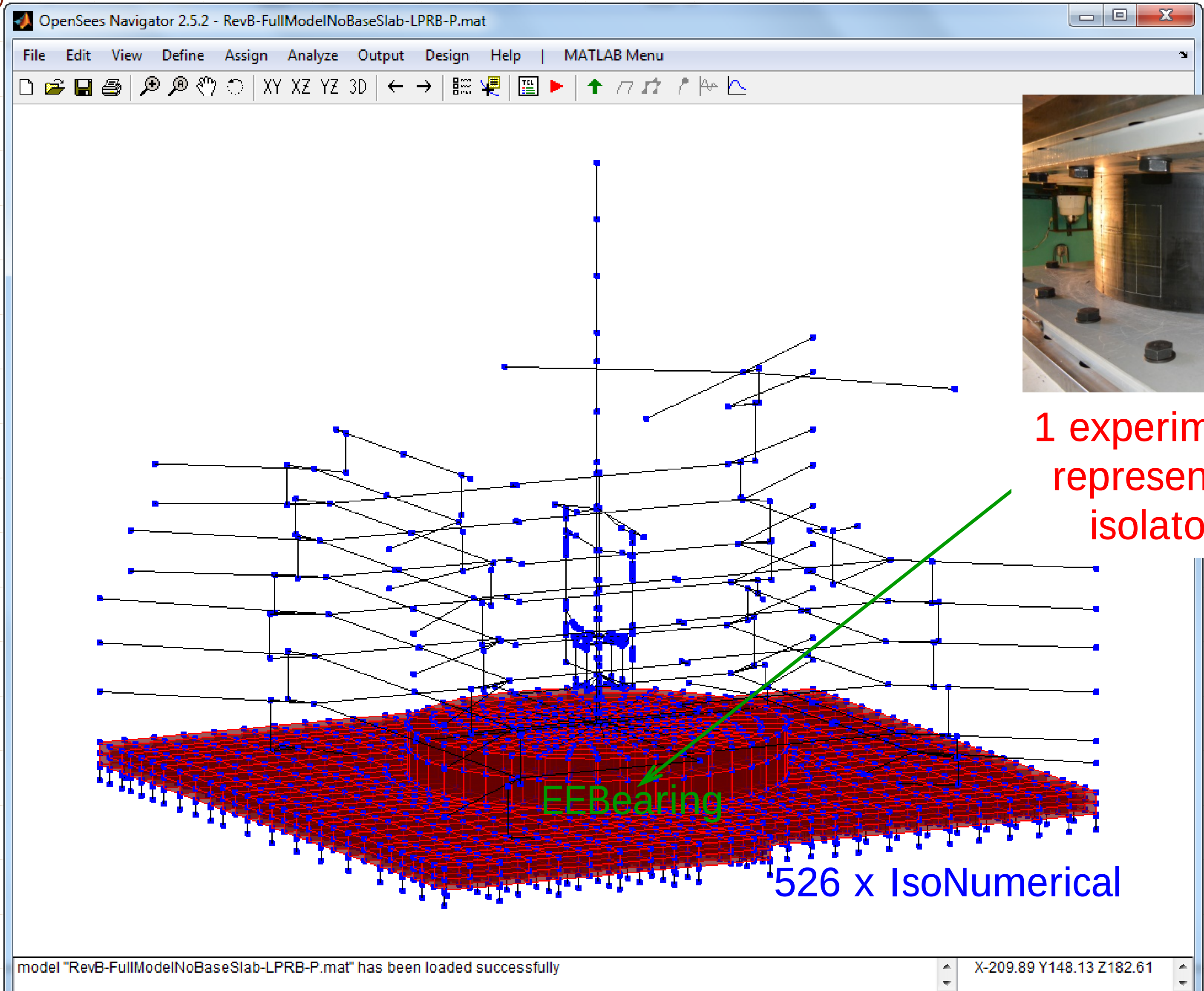
C) Model with 5 isolators (corner)

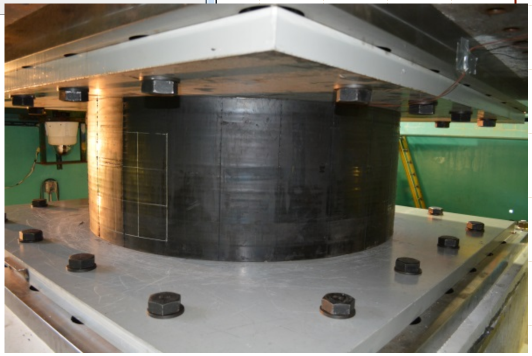




1 experimental isolator representing a group of isolators in corner

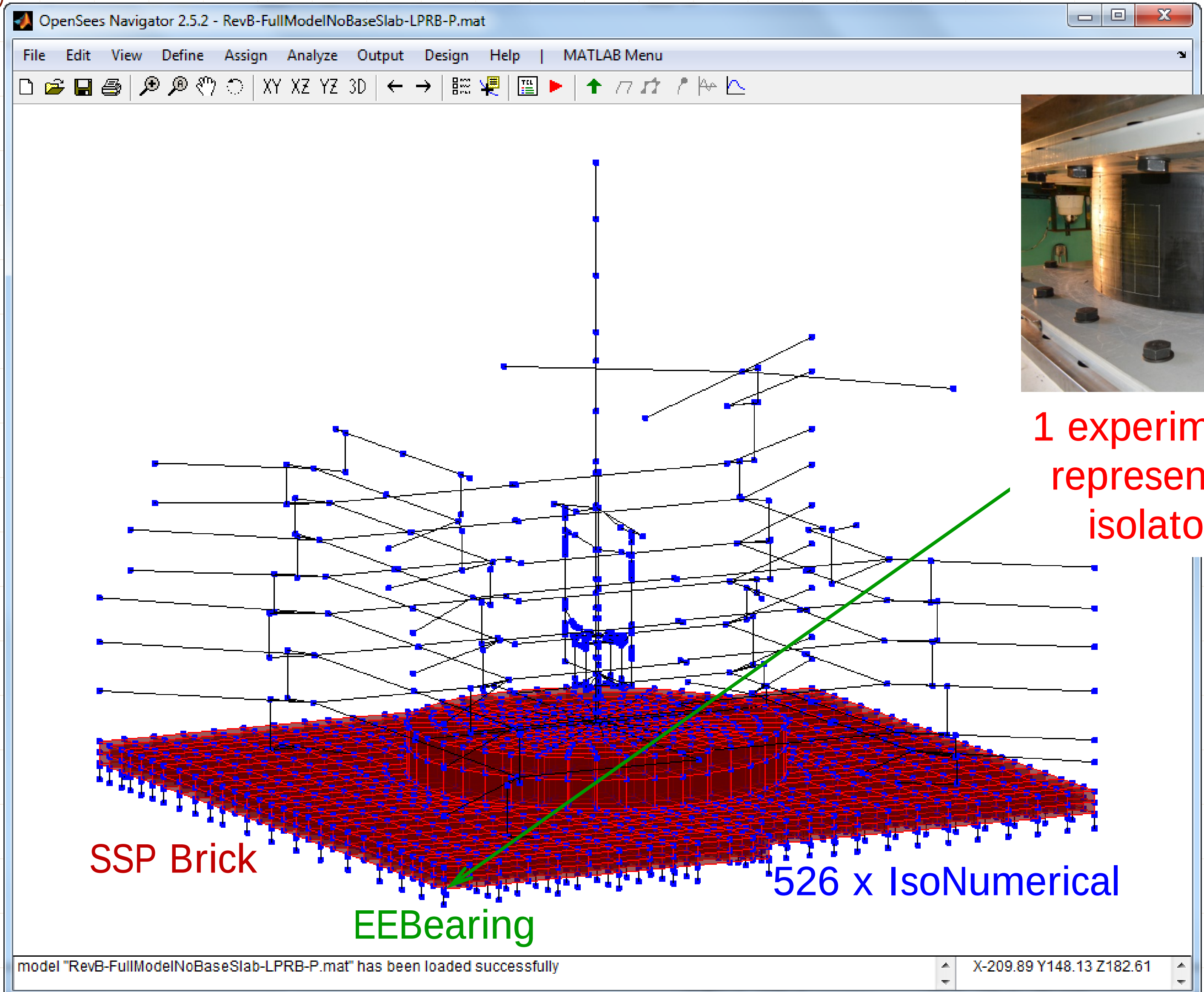
D) Model with 527 isolators (center)

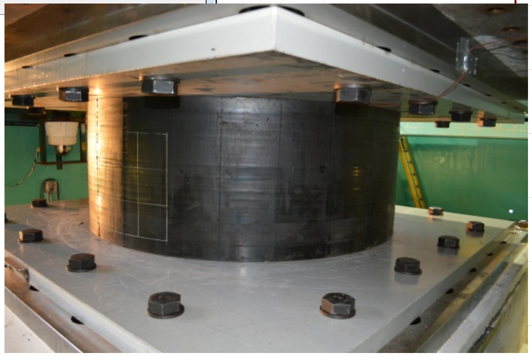




1 experimental isolator representing a single isolator in center

E) Model with 527 isolators (corner)

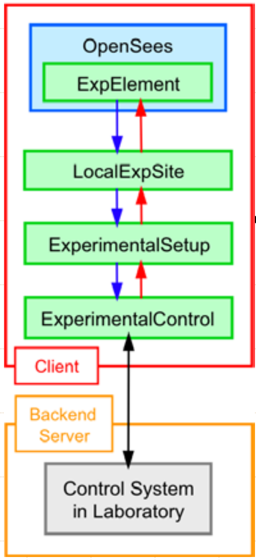


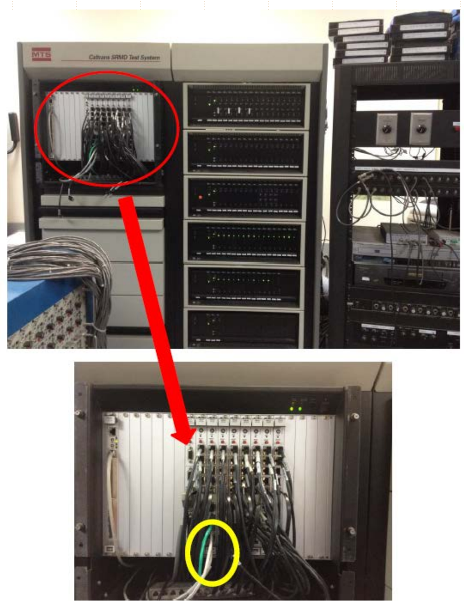


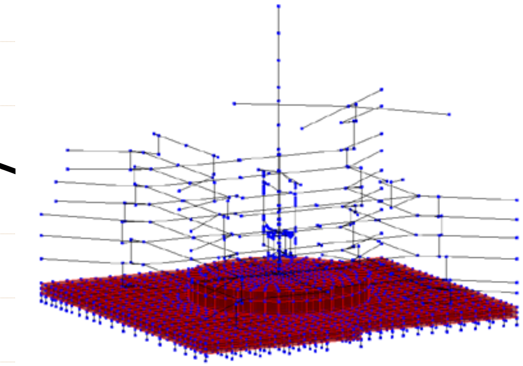
1 experimental isolator representing a single isolator in center

OpenSees/OpenFresco Details

OpenSees and OpenFresco Details







OpenSees Finite Element Model

OpenFresco Middleware

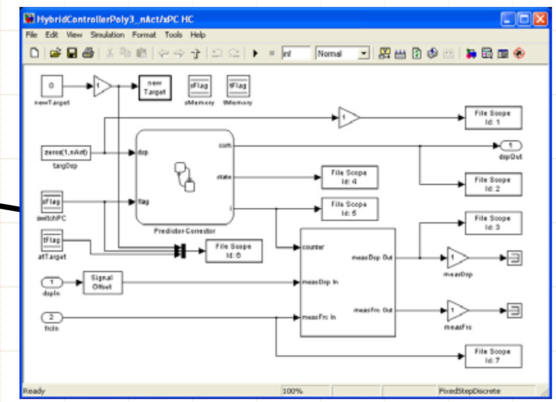
CLIB API

dSPACE real-time Predictor-Corrector

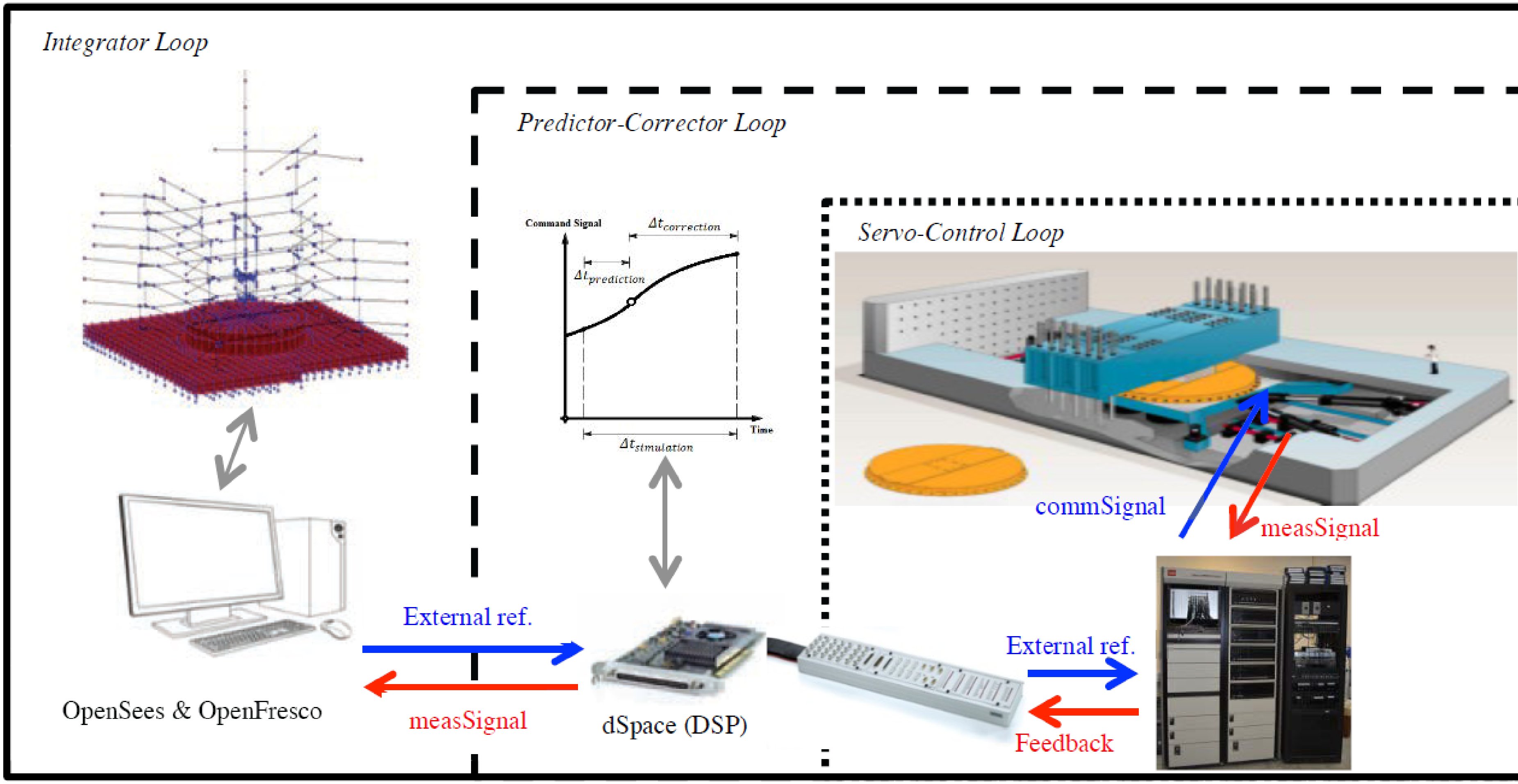
Analog BNC

MTS SRMD real-time Controller

Physical Specimen in Laboratory



Three-Loop Hardware Architecture



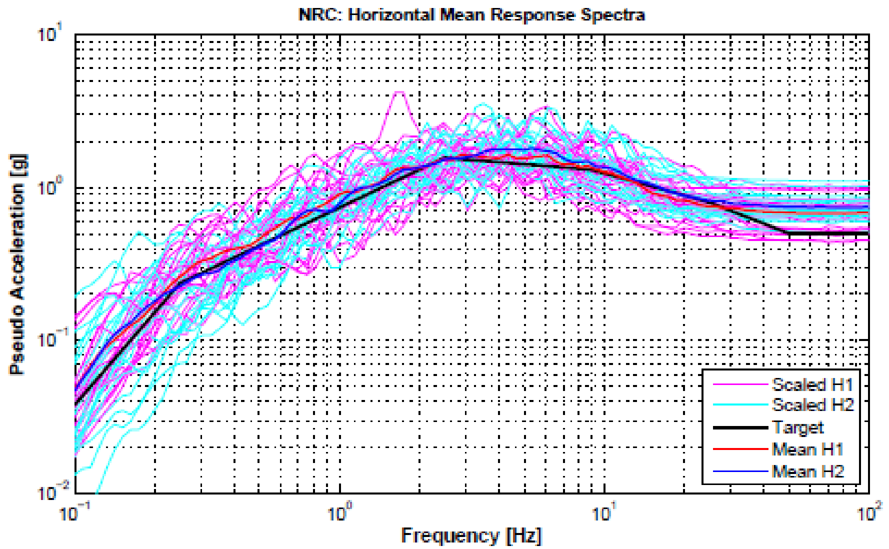
dt_{int} = 0.01 sec, dt_{sim} = 0.25 sec (0.05 sec), dt_{con} = 0.001 sec

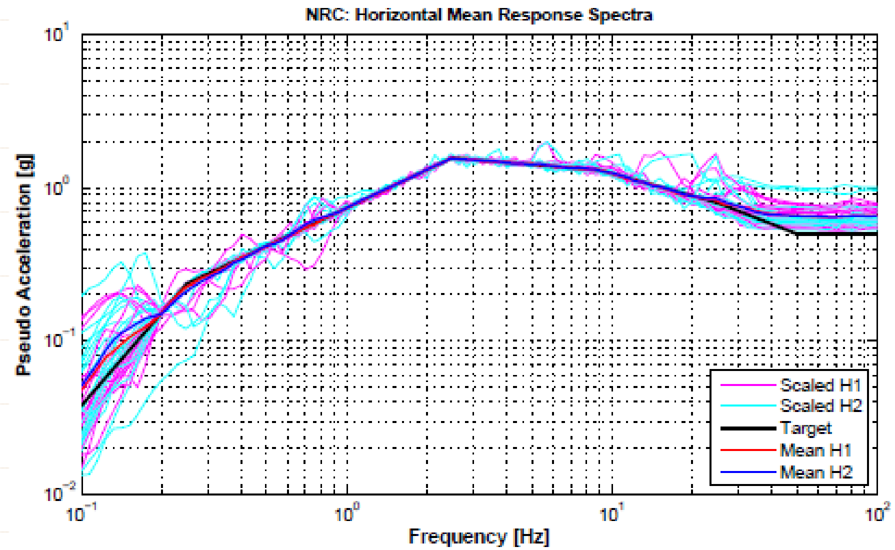
OpenSees and OpenFresco Details

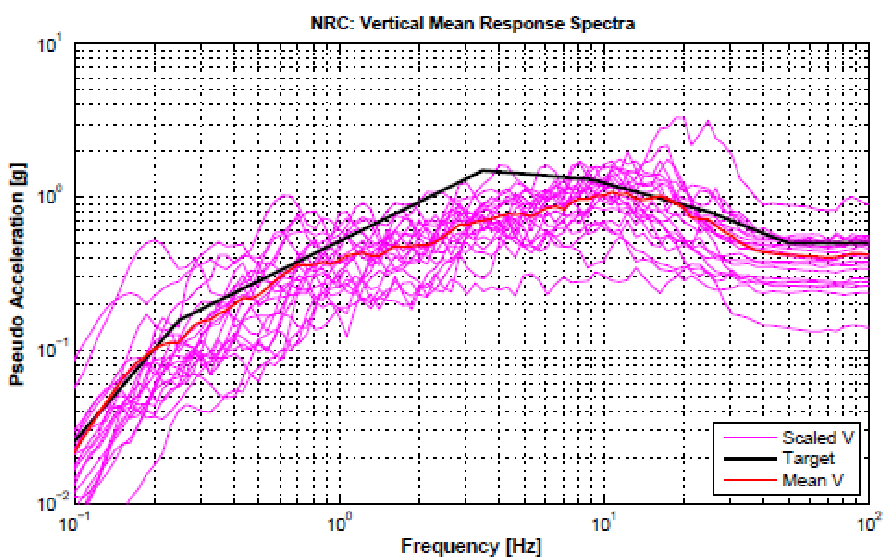
- First-time use of OpenSeesSP for HS
- All integrators specialized for HS are now available in OpenSeesSP
- Added new command “partition $eleTag”
- Execution on high performance overclocked 12-core analysis machine
- Hybrid models with several thousand DOF can be tested in real-time
- If system is linear command “algorithm Linear –factorOnce” can be used

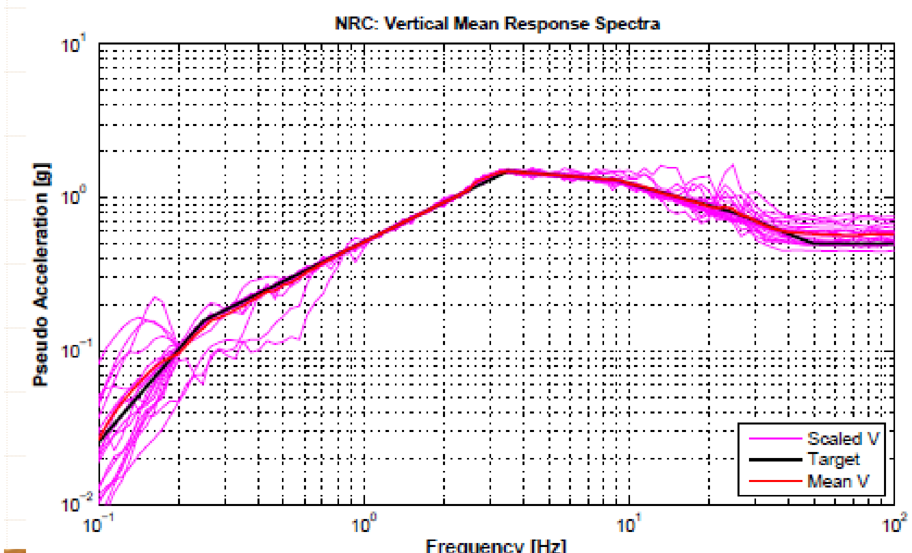
Ground Motions

NRC DA & SMSD: PsdAcc Response Spectra

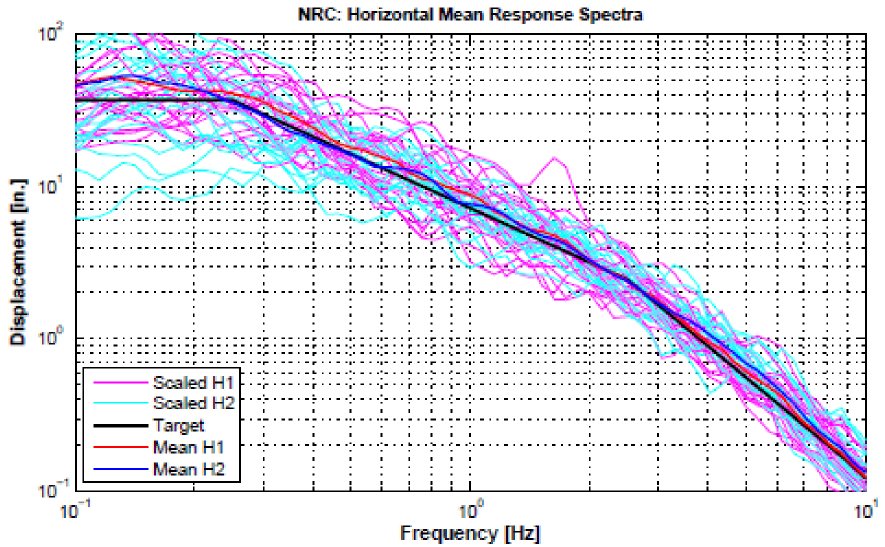


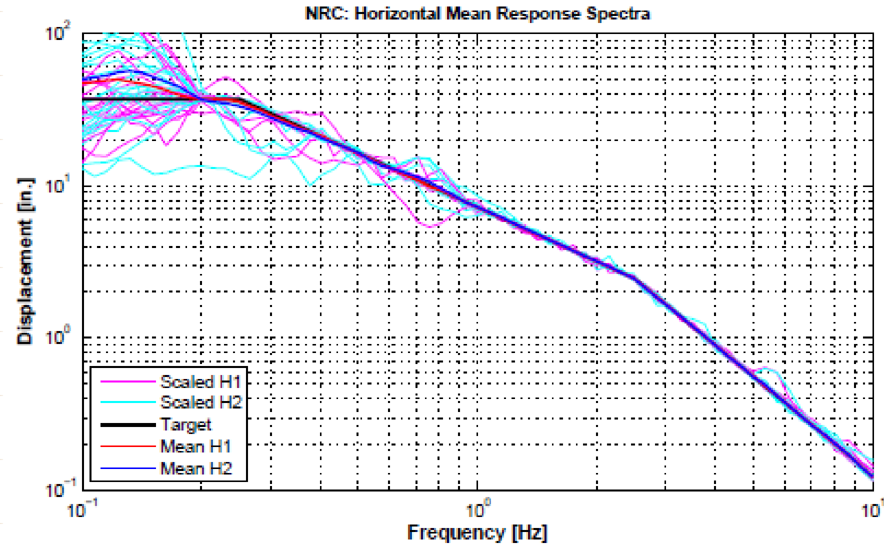


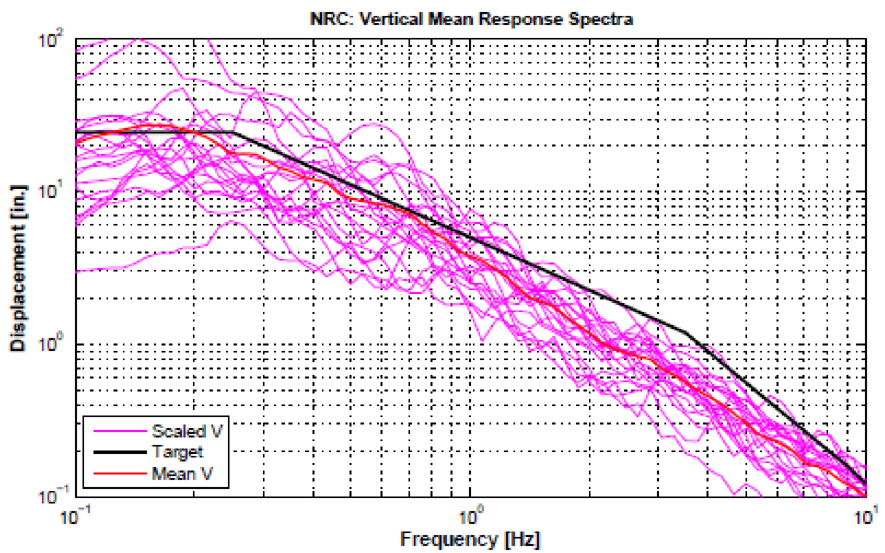


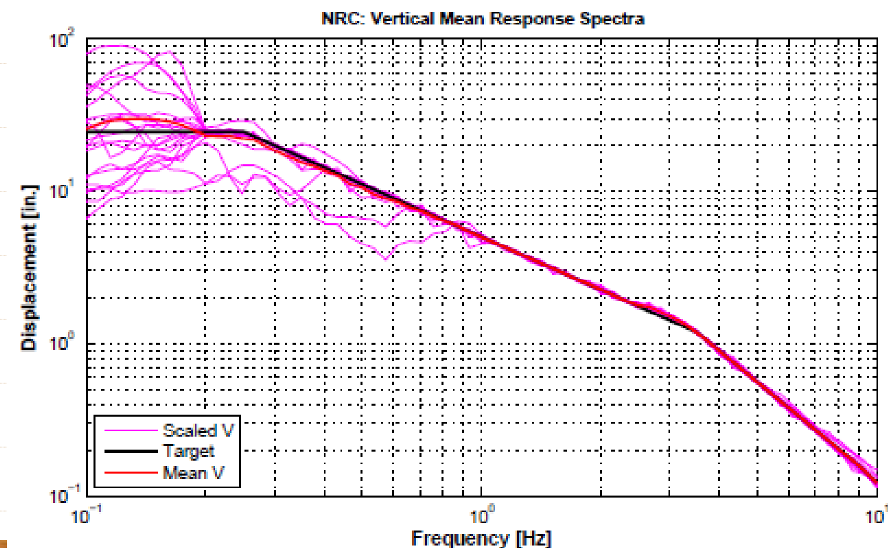


NRC DA & SMSD: Displ. Response Spectra

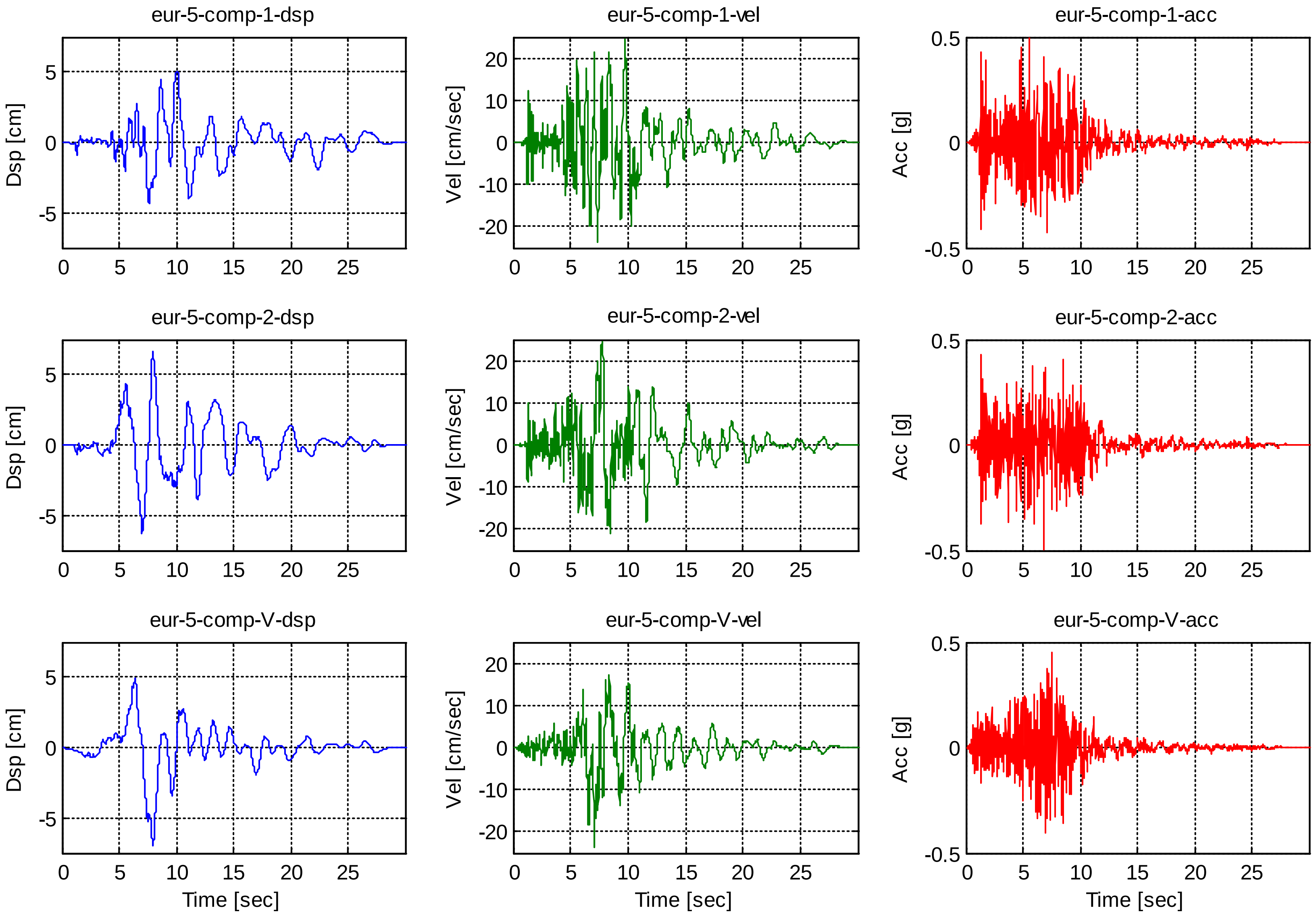




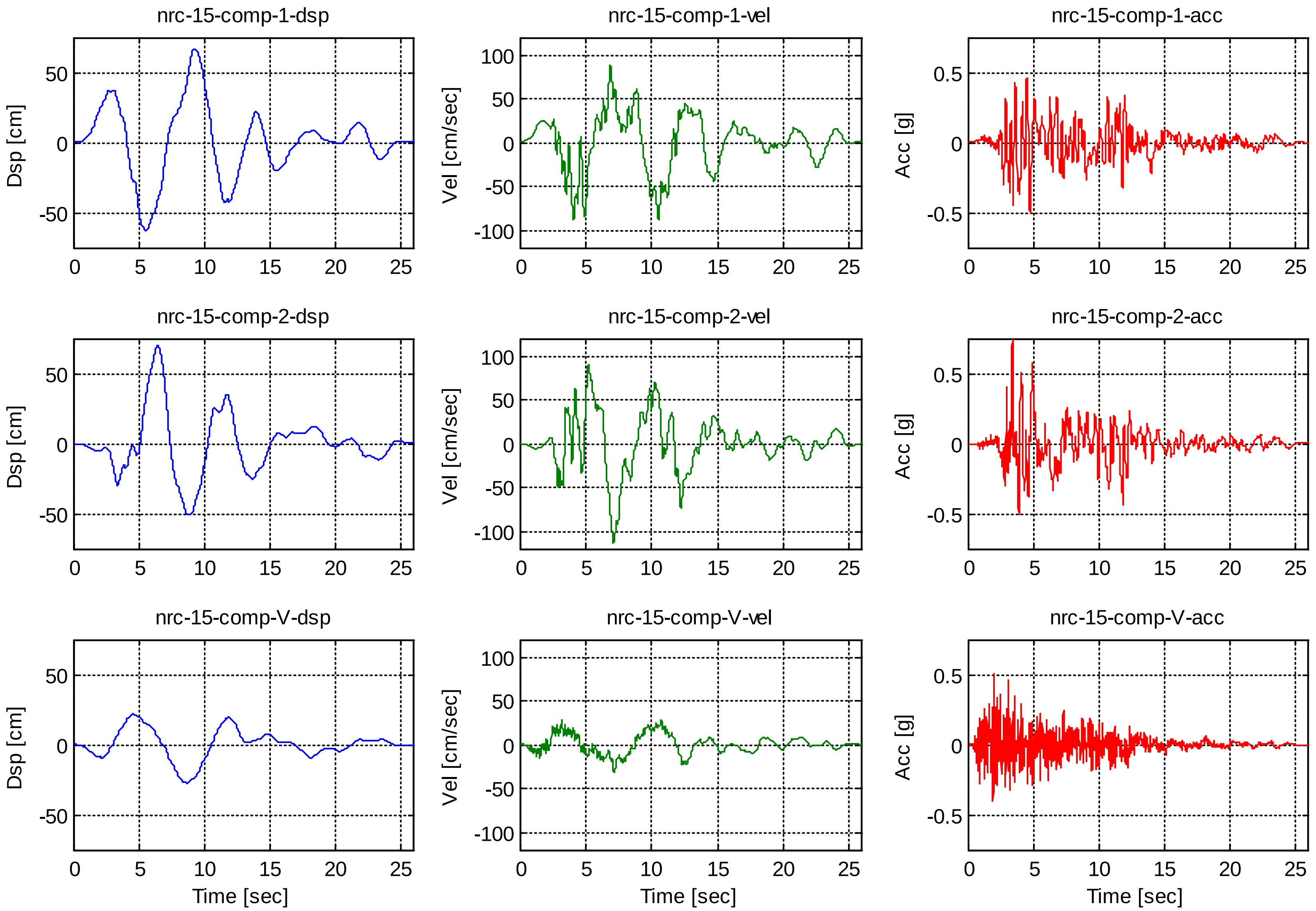




EUR 5 Ground Motion

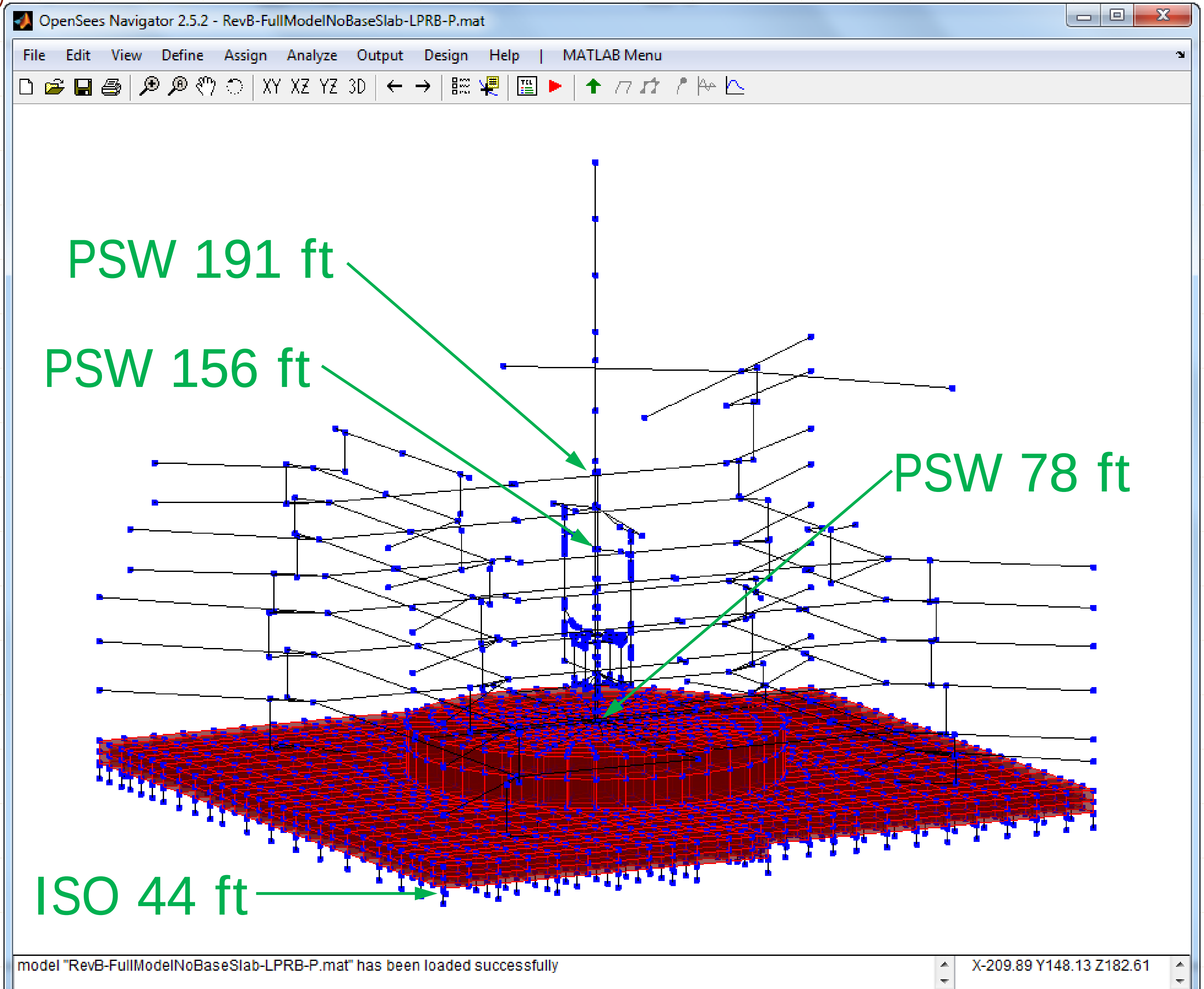


NRC 15 Ground Motion

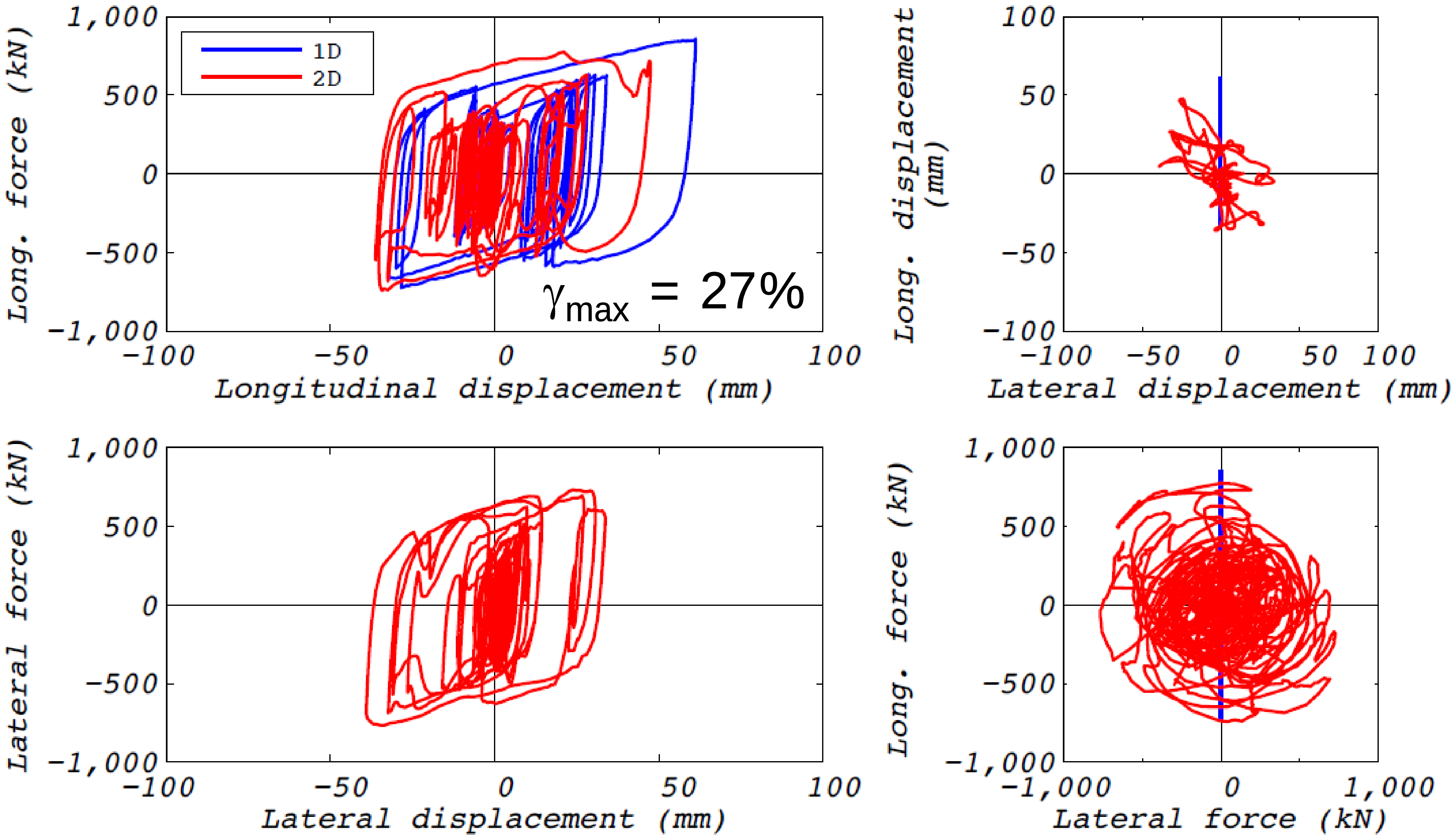


Test Results

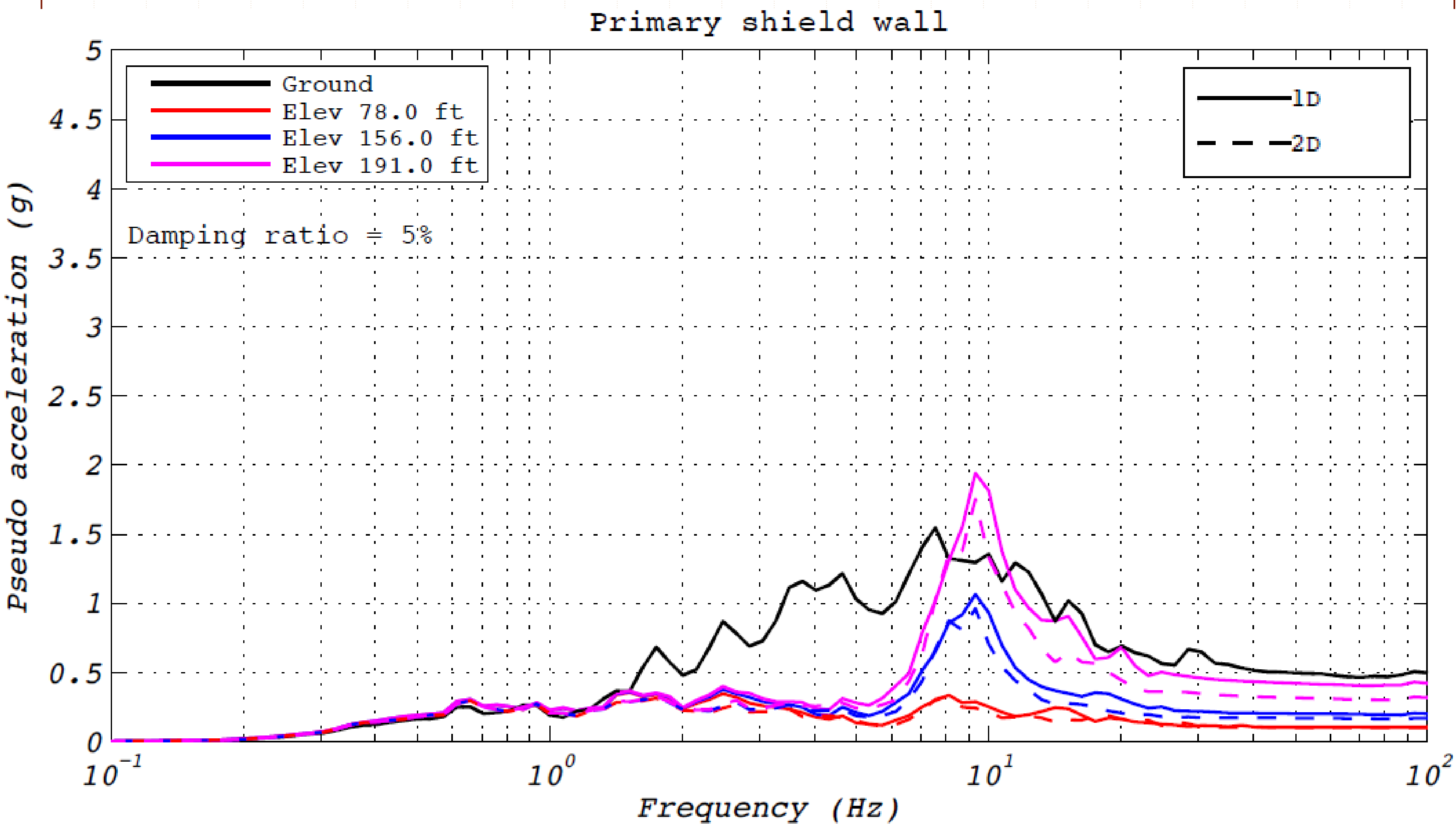
Result output locations



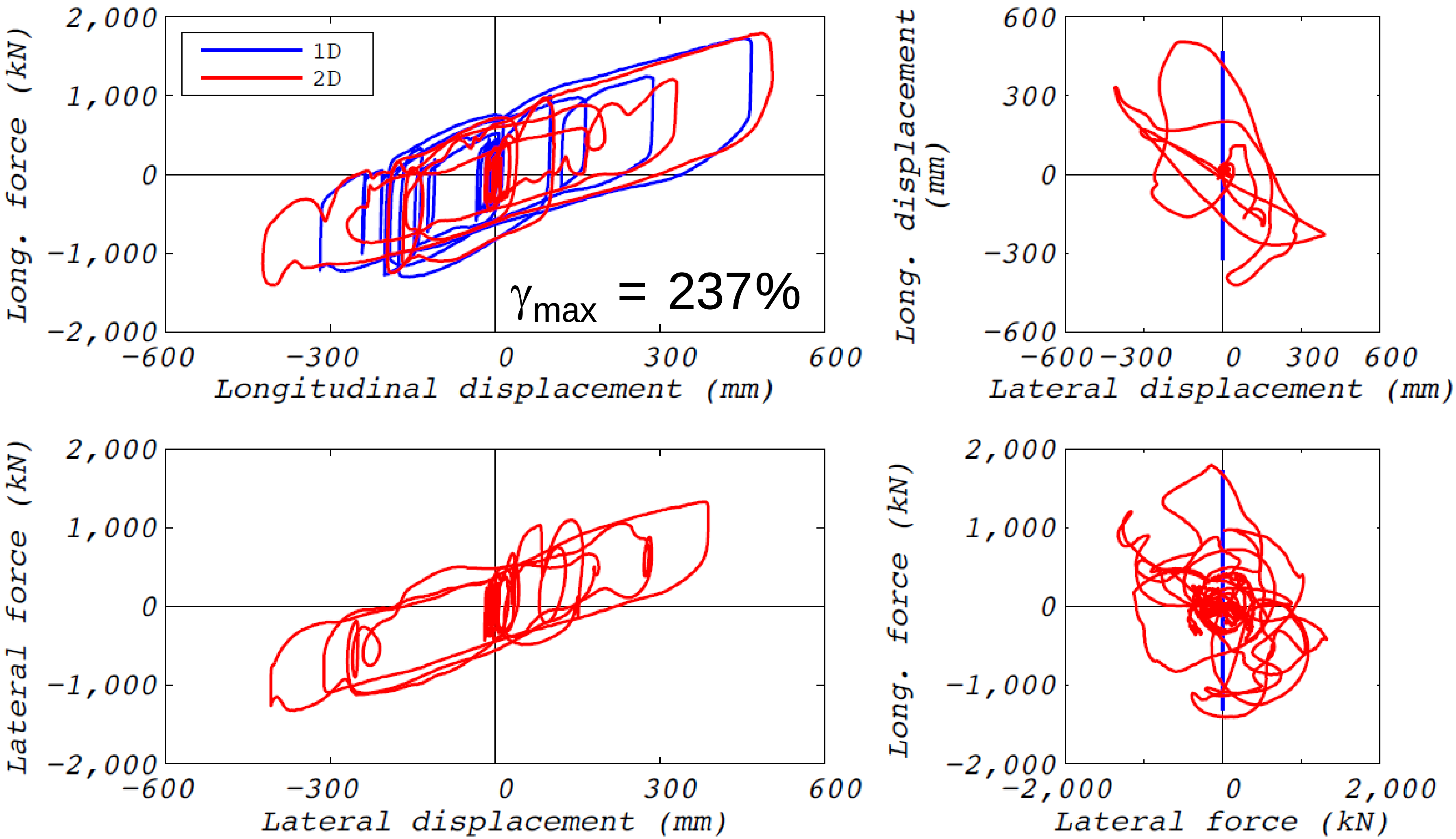
1D vs. 2D horizontal input (EUR)



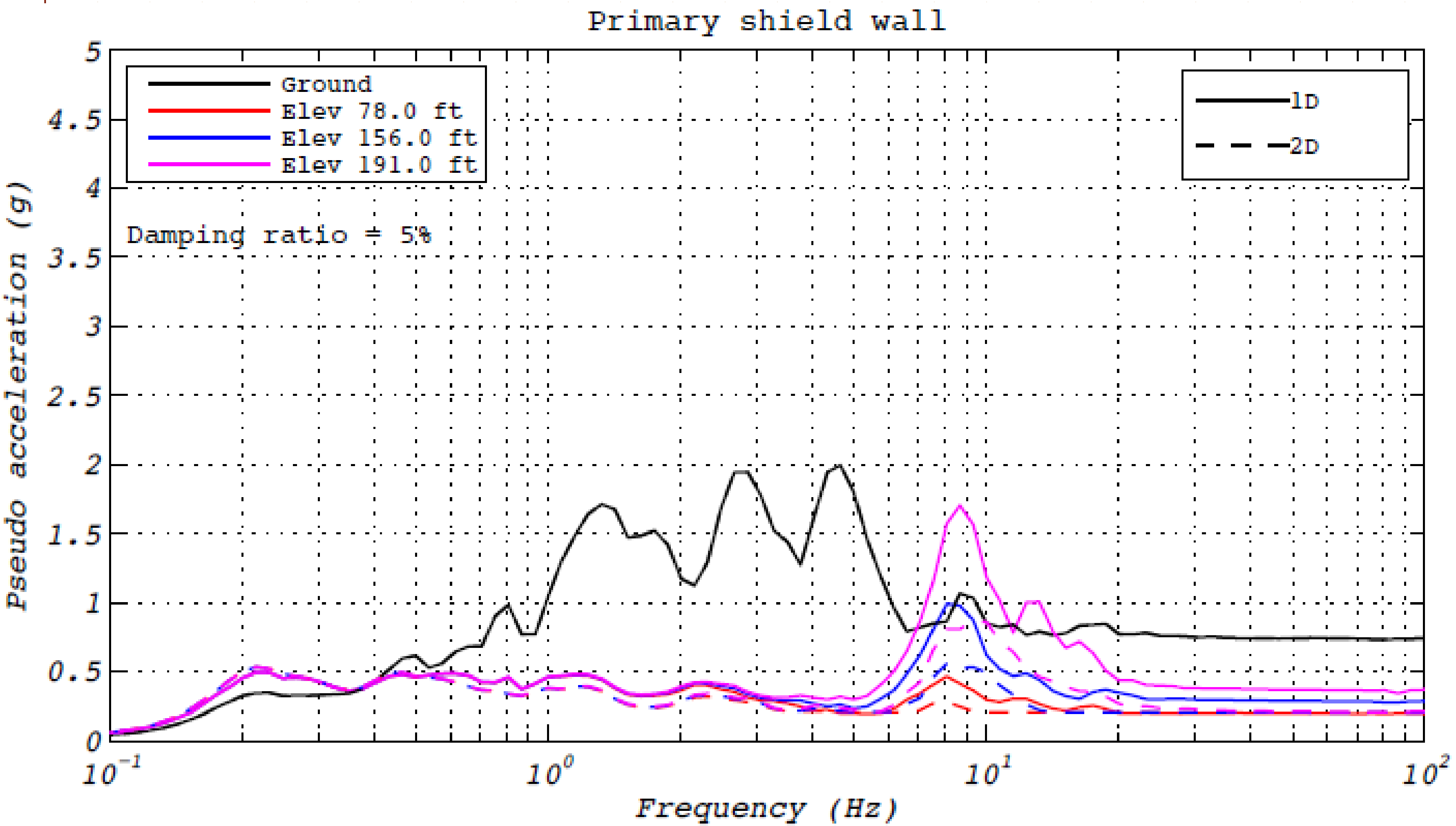
1D vs. 2D horizontal input (EUR)



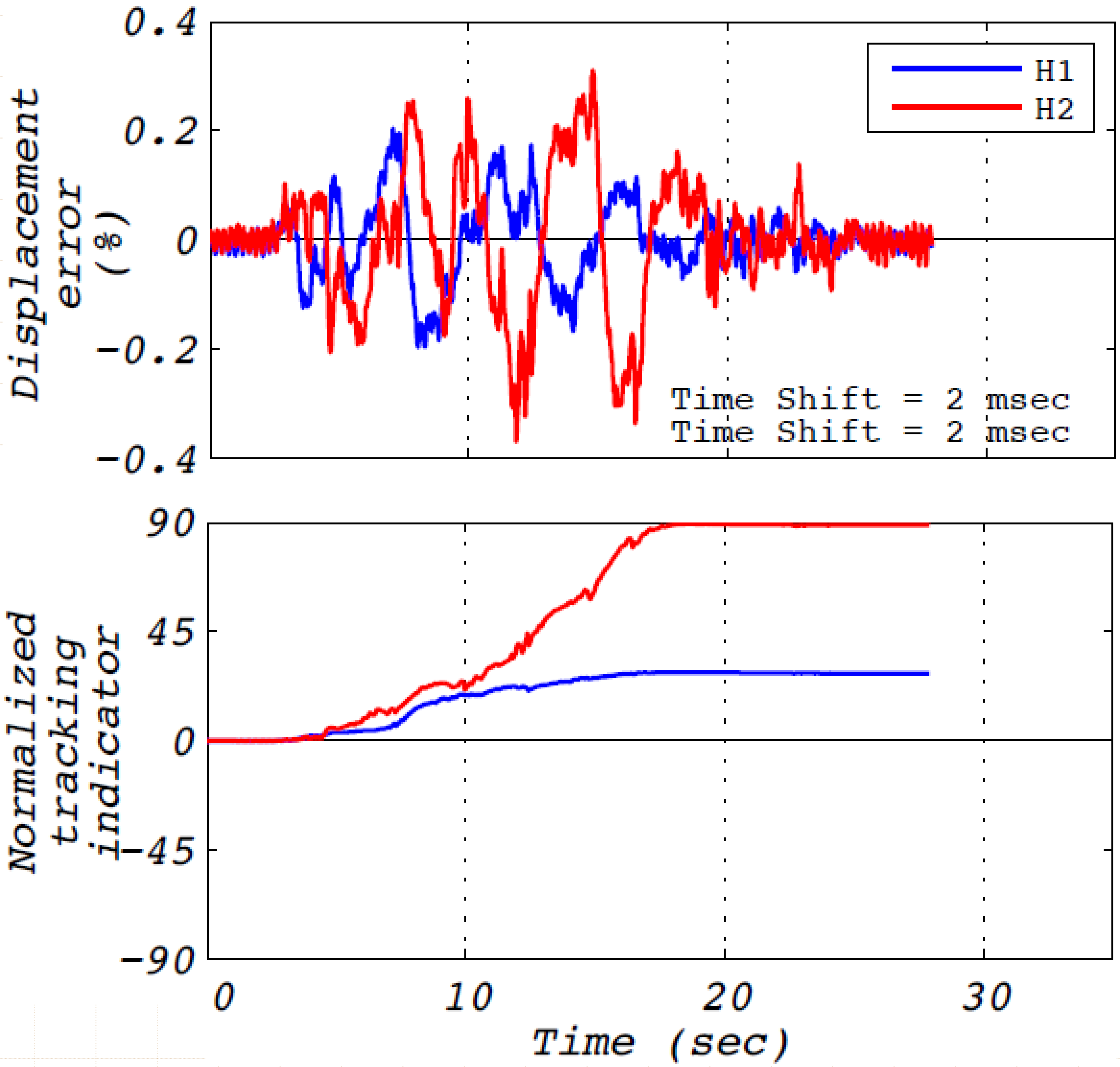
1D vs. 2D horizontal input (NRC)



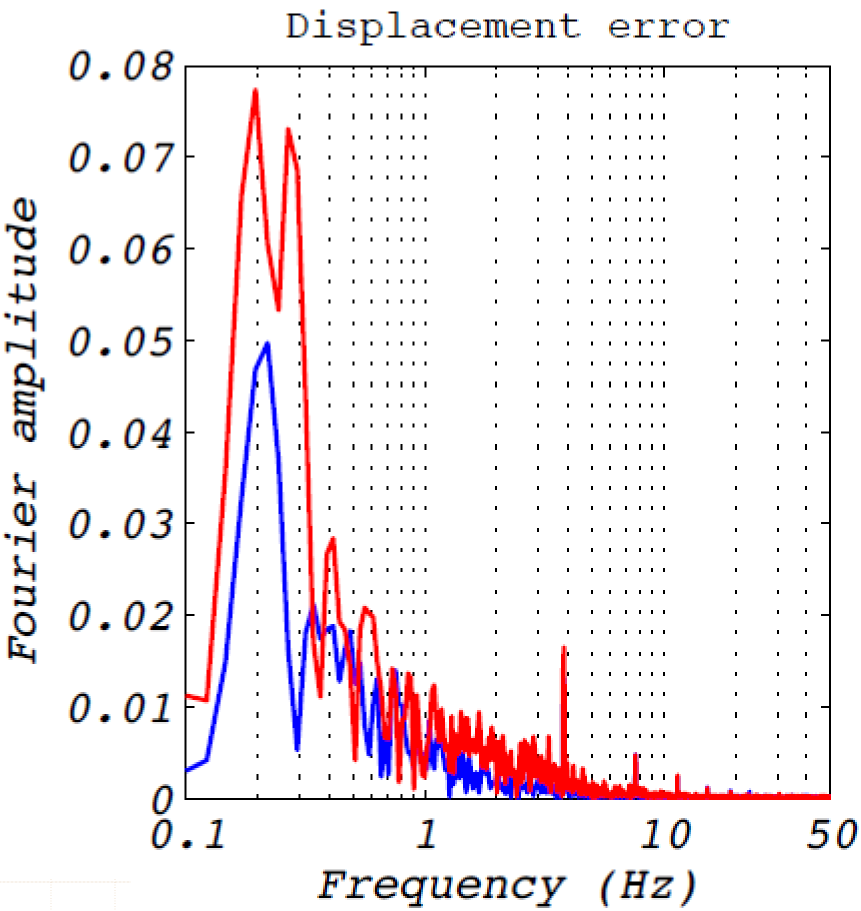
1D vs. 2D horizontal input (NRC)

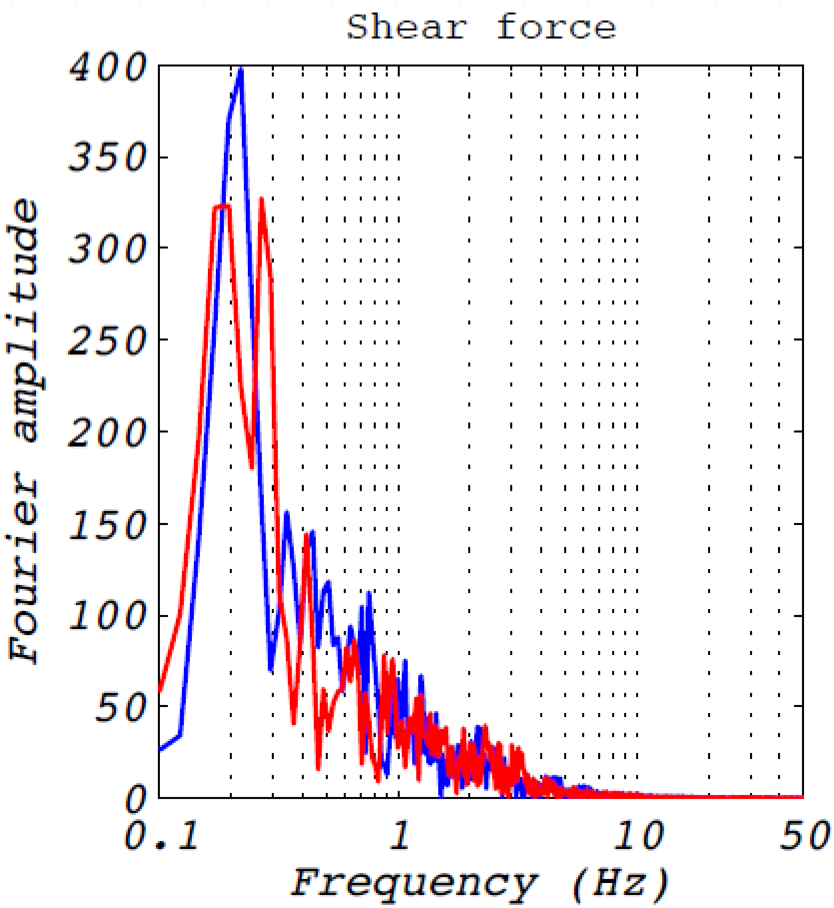


Error monitors for 2D test

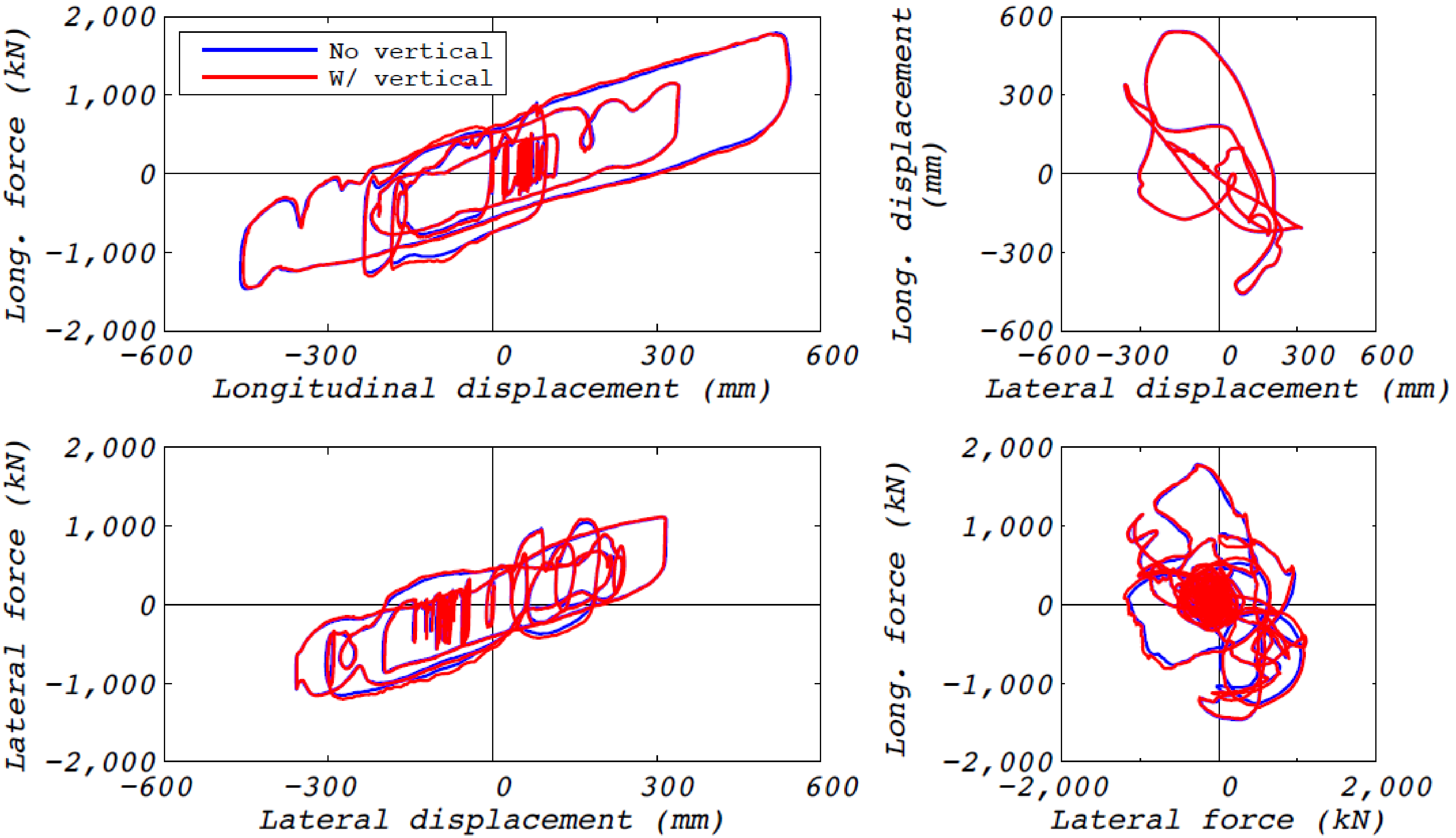


Error monitors for 2D test

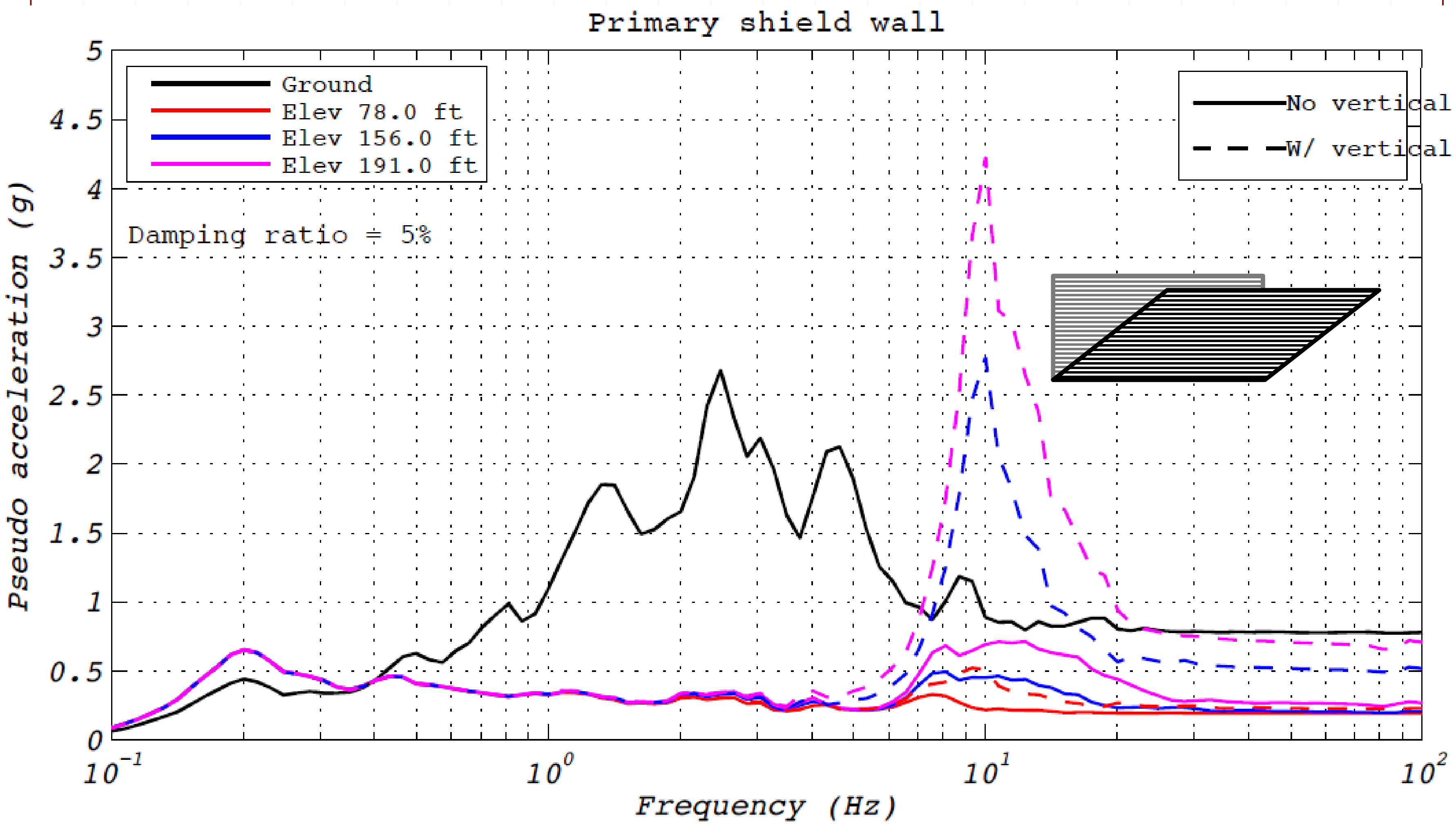




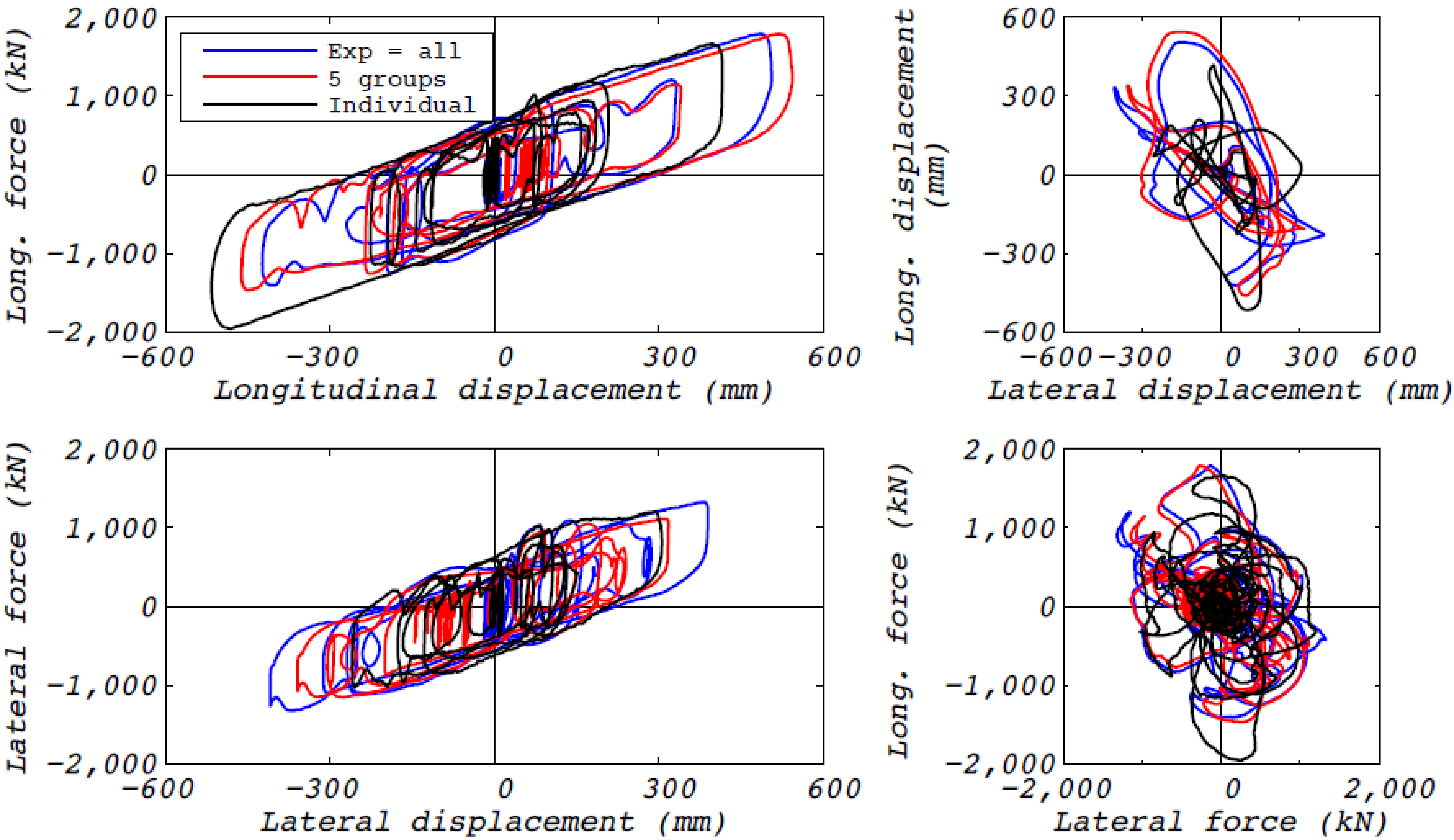
w/o versus w/ vertical input



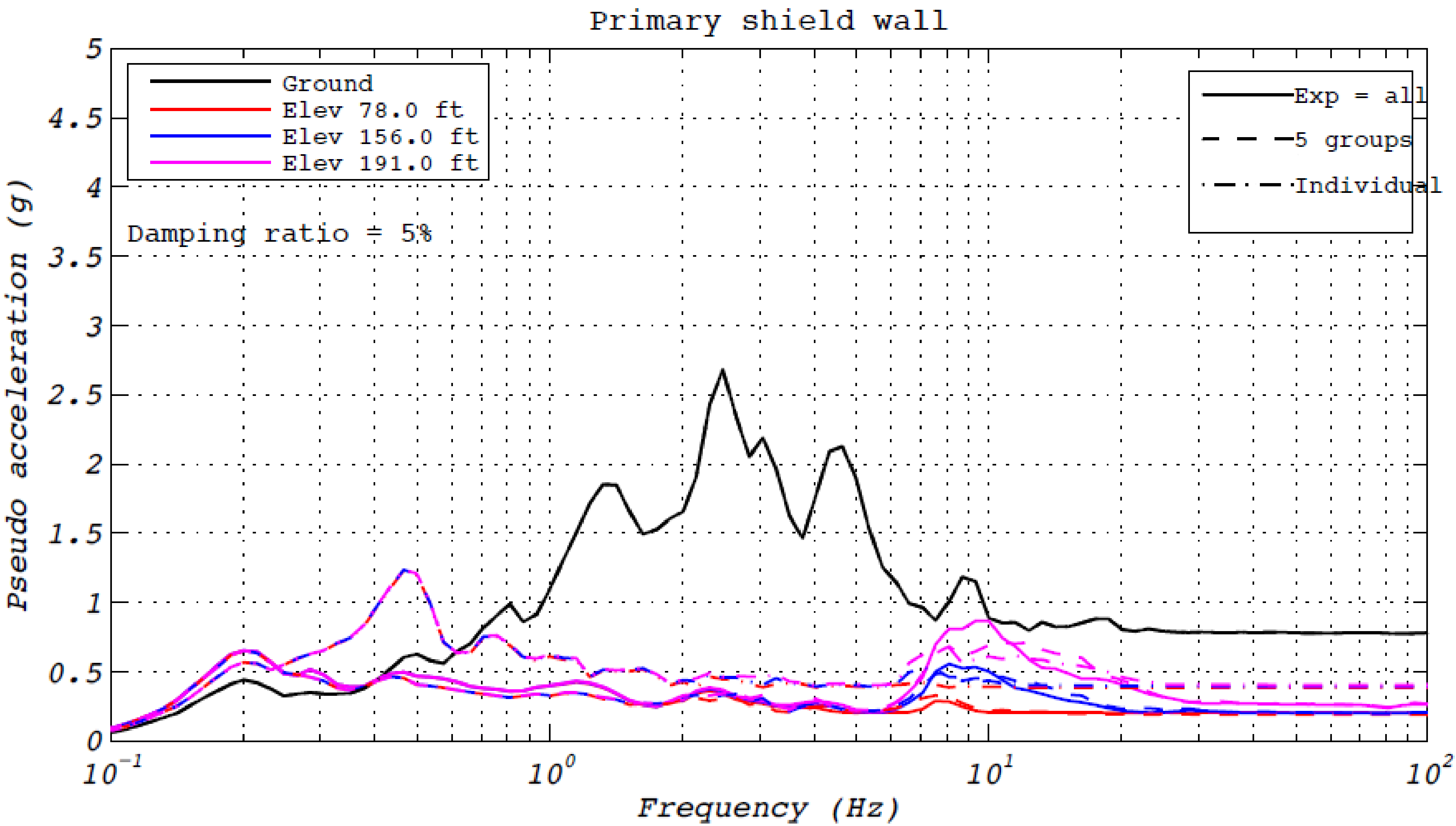
w/o versus w/ vertical input



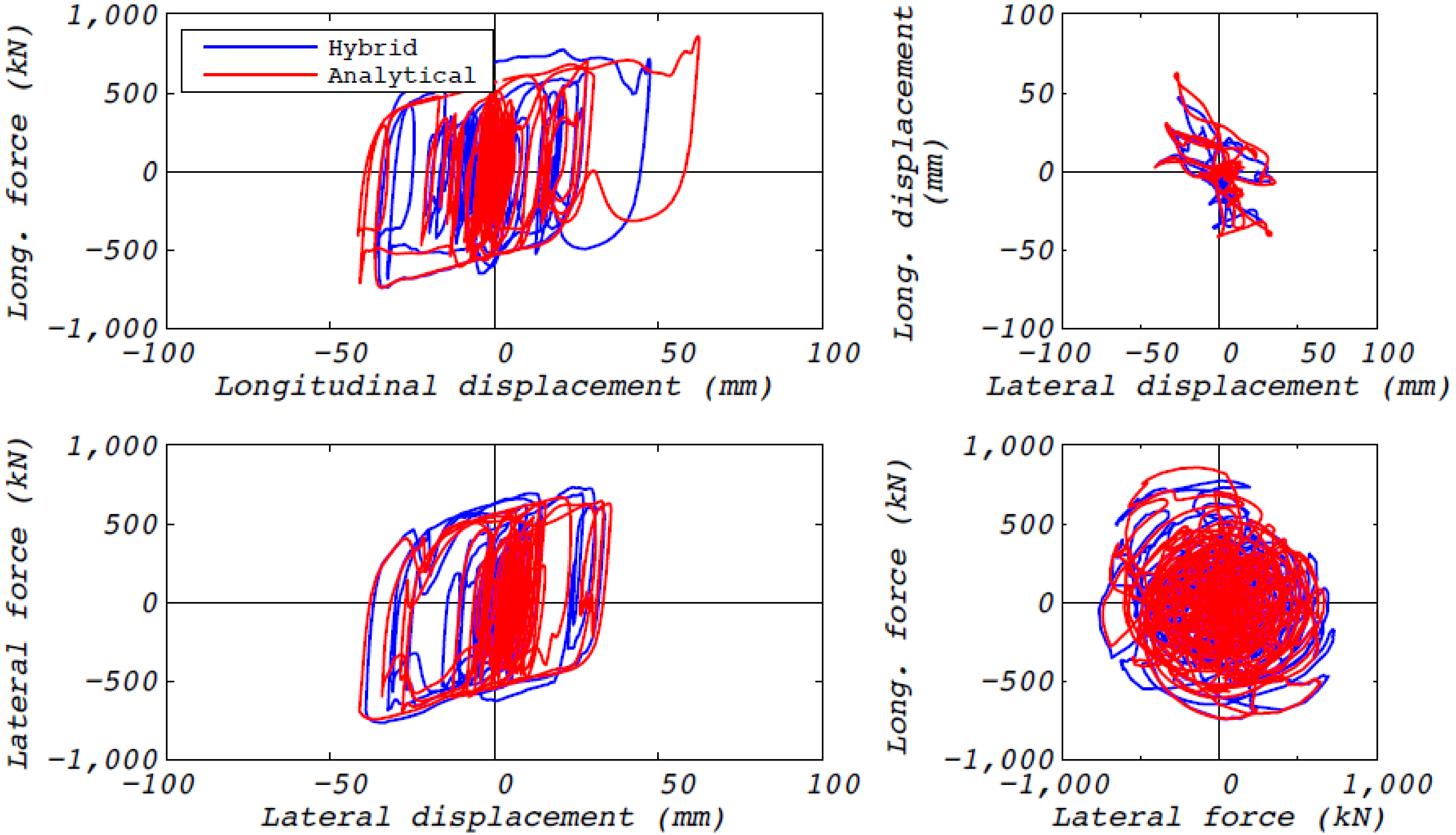
Bearing layout discretization



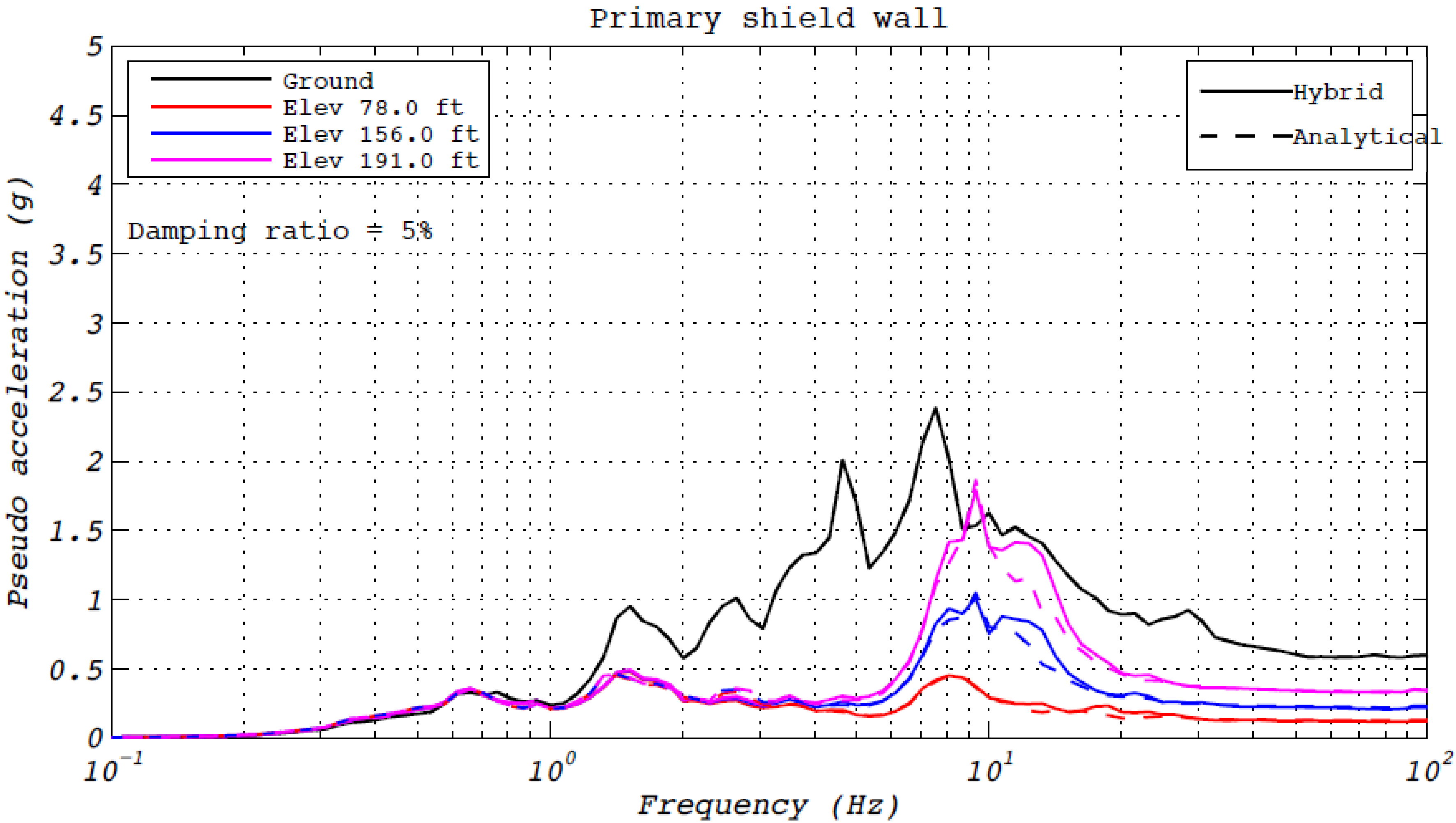
Bearing layout discretization



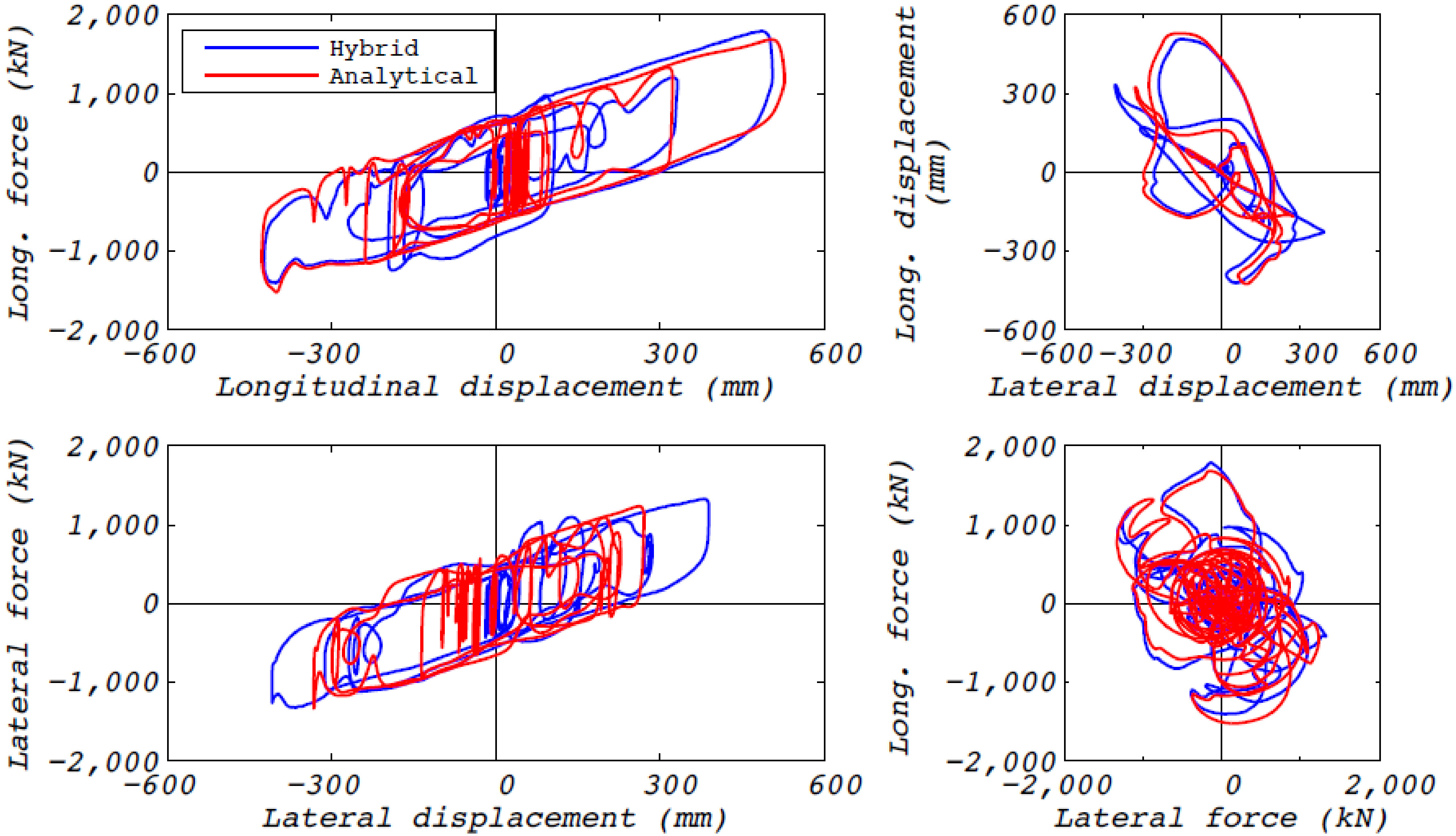
Hybrid vs. Analytical (EUR)



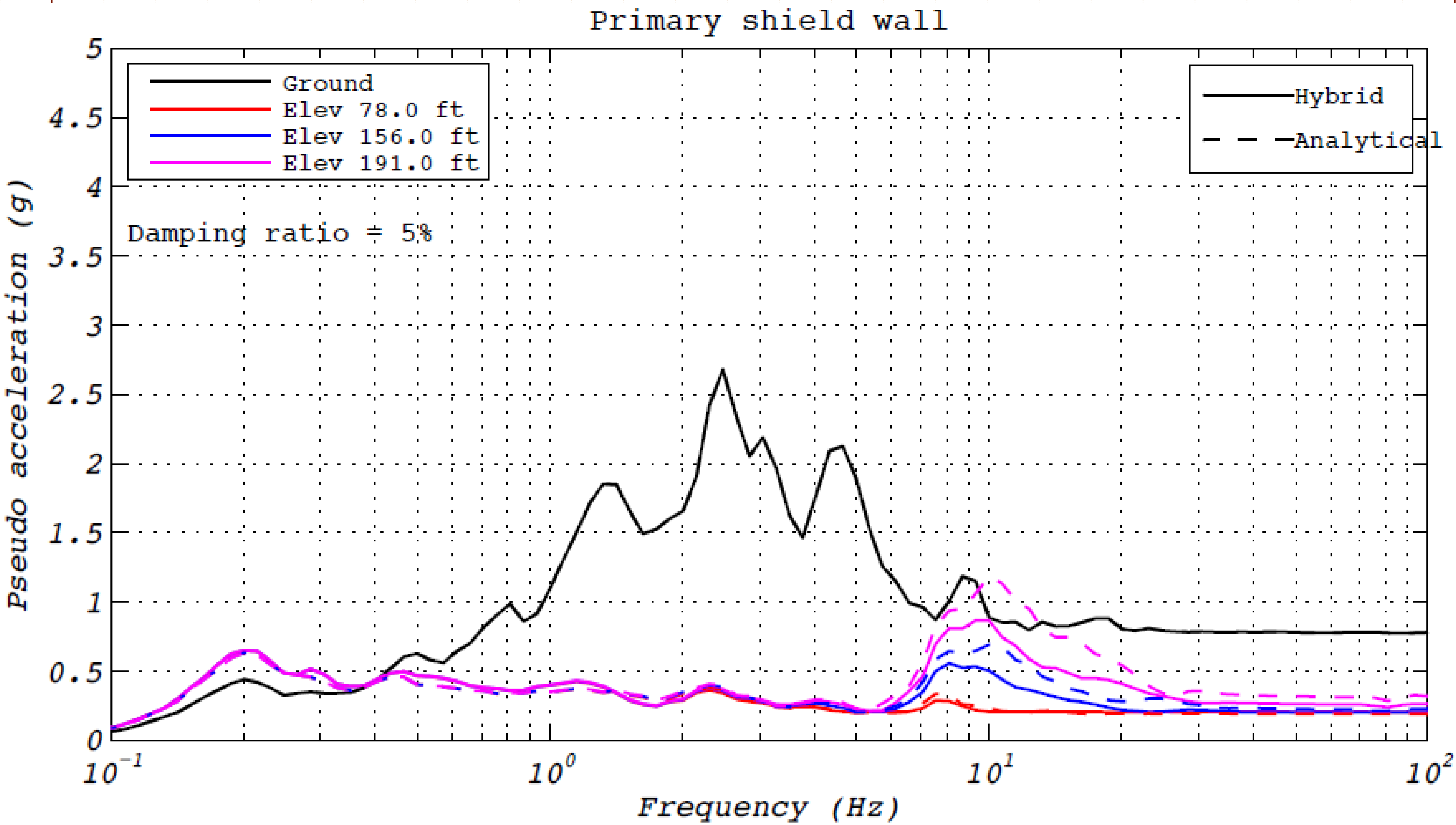
Hybrid vs. Analytical (EUR)



Hybrid vs. Analytical (NRC)

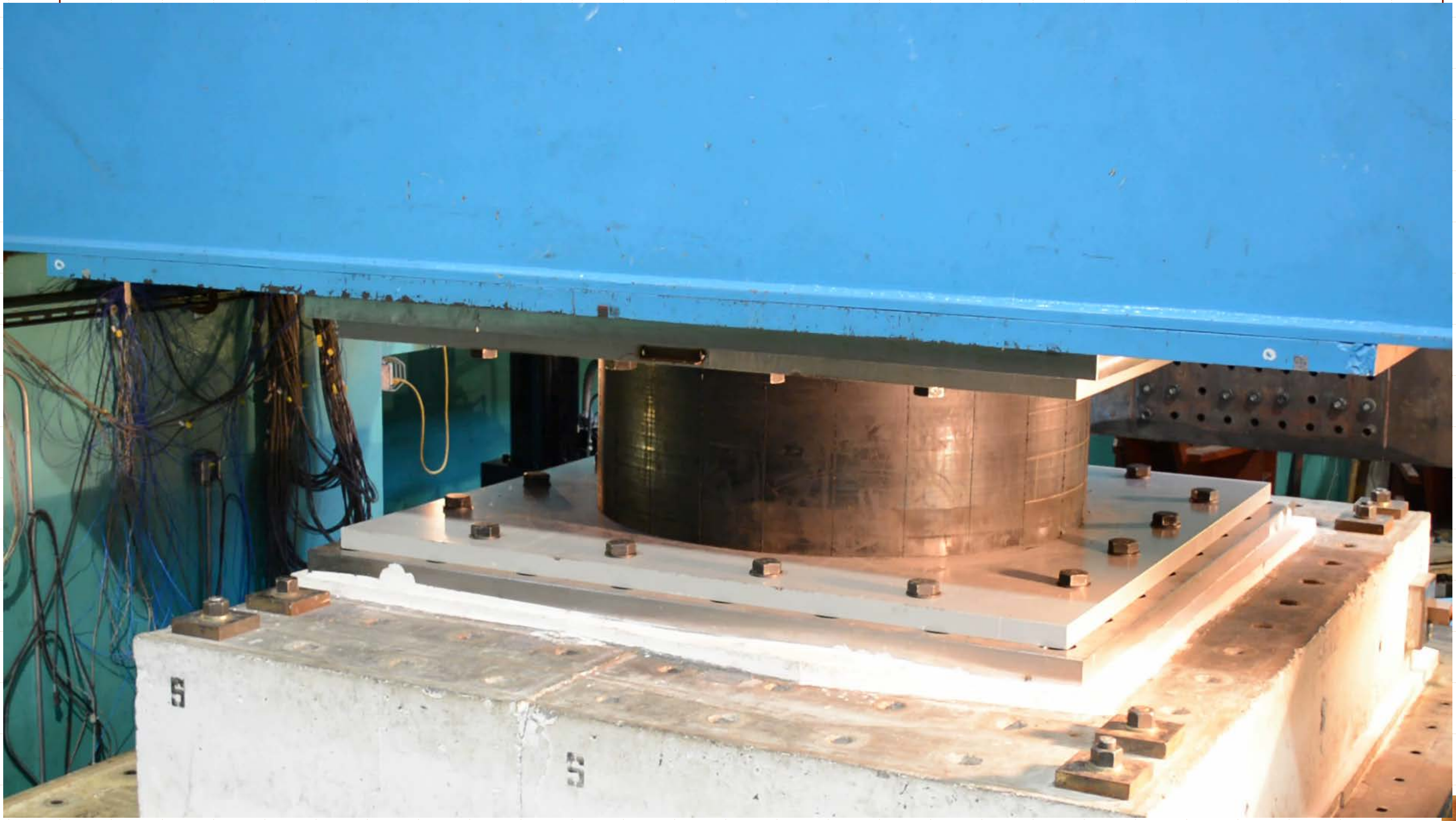


Hybrid vs. Analytical (NRC)



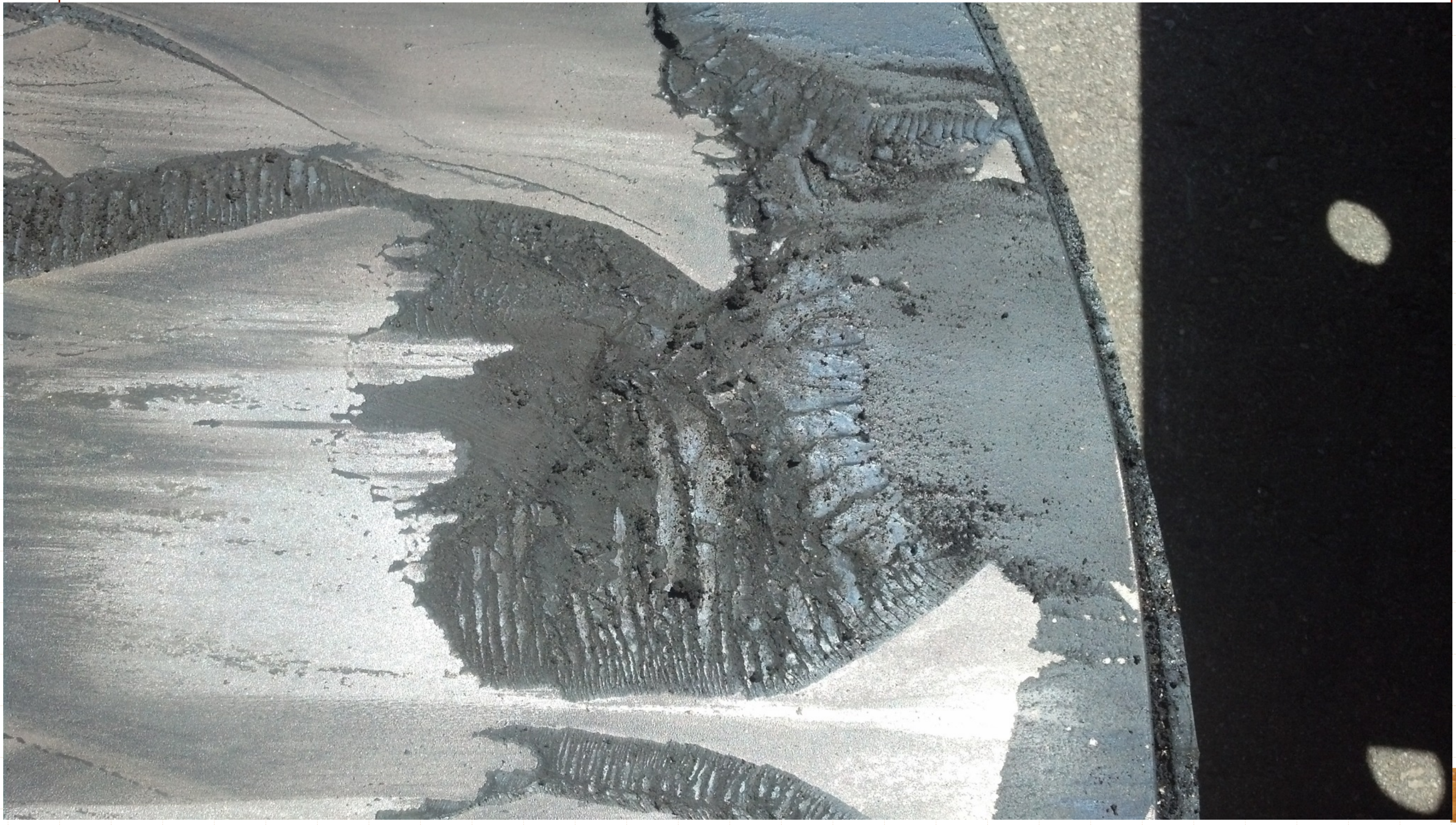
LPRB and EQSB Failure Tests

Movie of 2D cyclic failure test



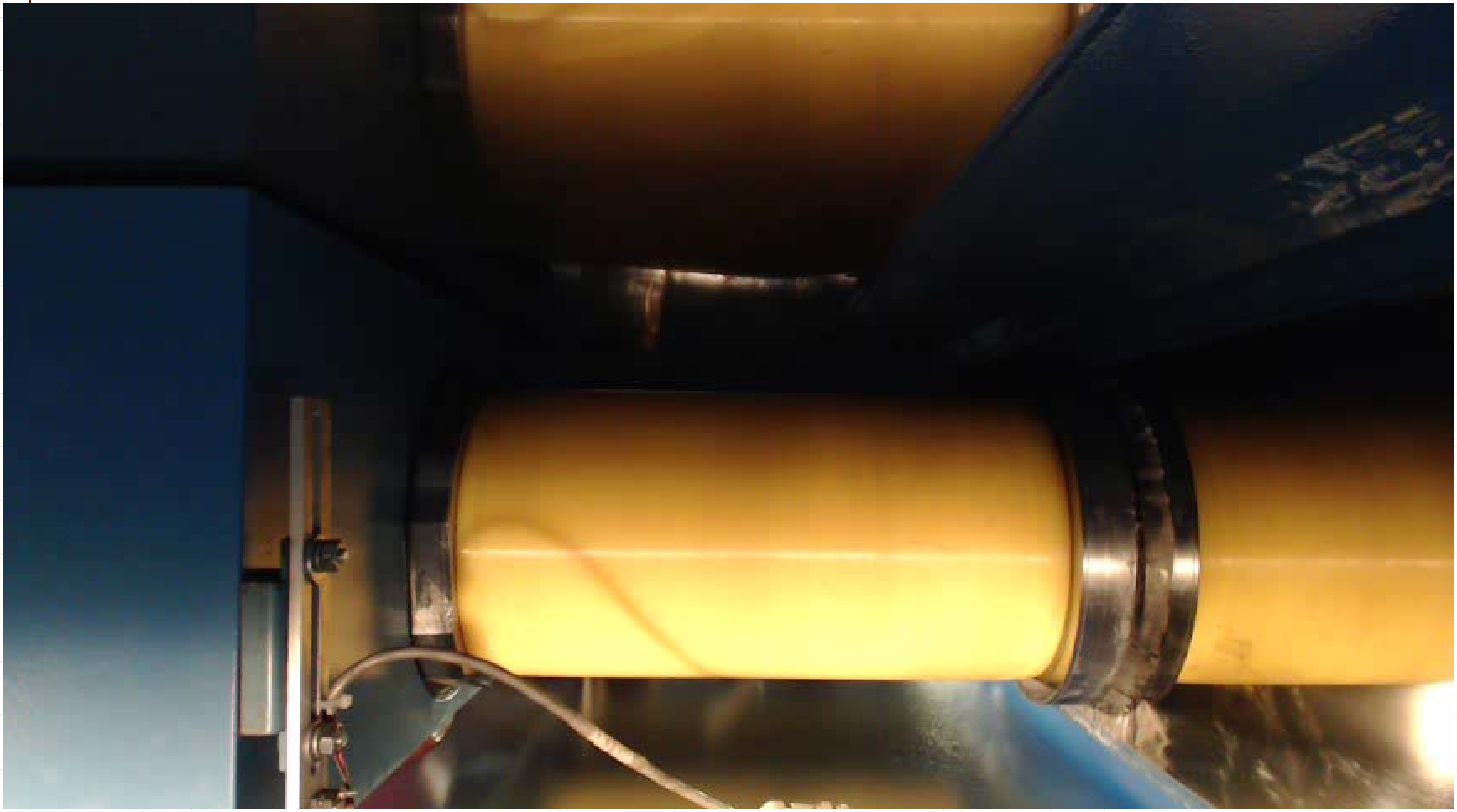
LPRB after ~400% shear strain failure

Close up of leading edge



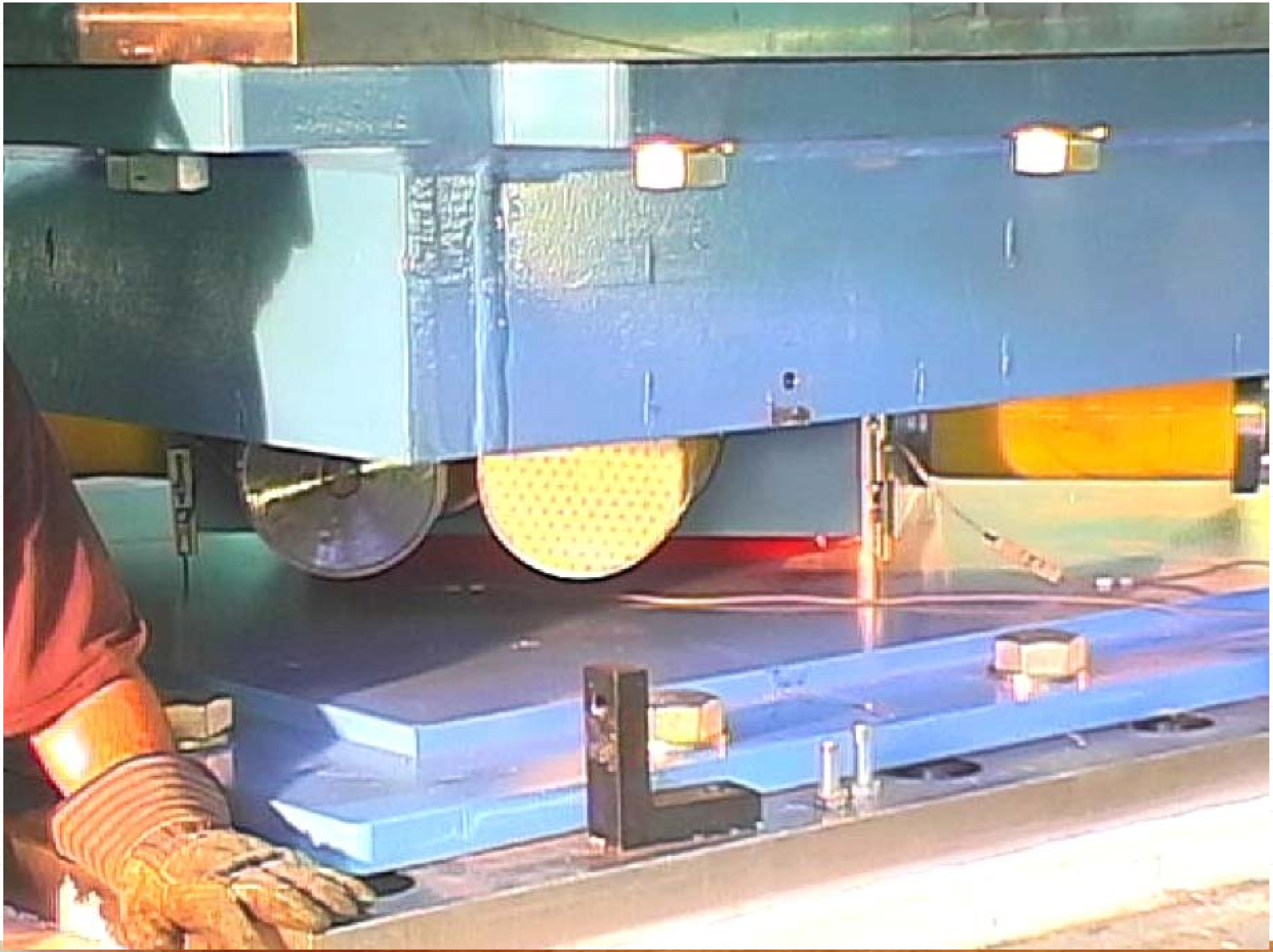
Close up of lead core

EQS test for 2D EUR 5 motion



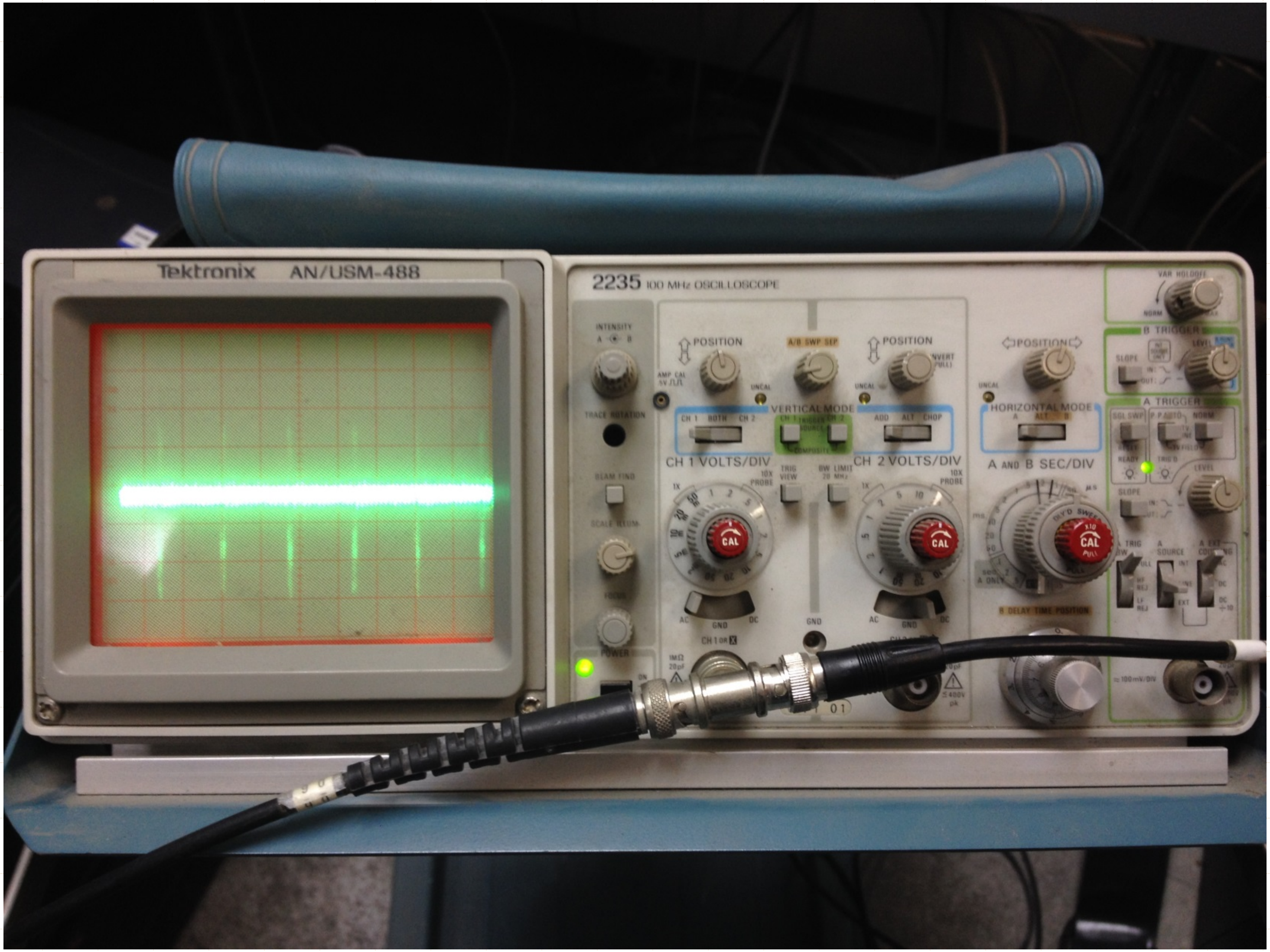
Rotated EQS slider

Rotated EQS slider

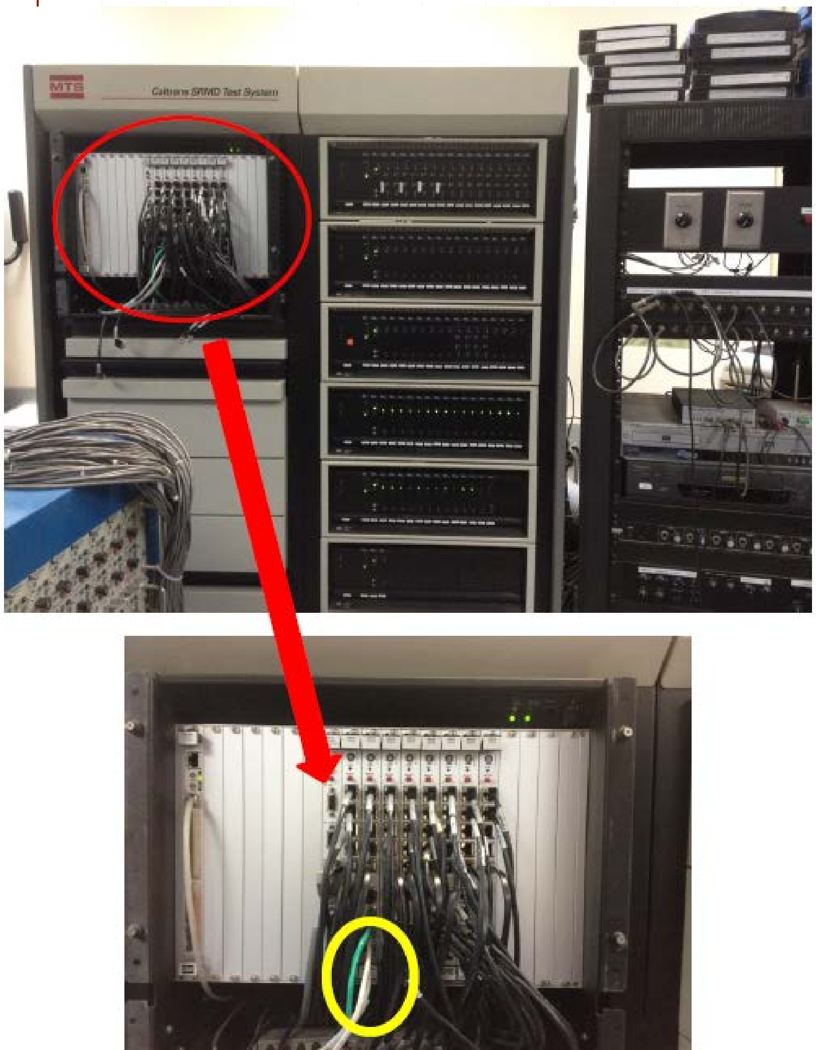


Problems and Resolutions

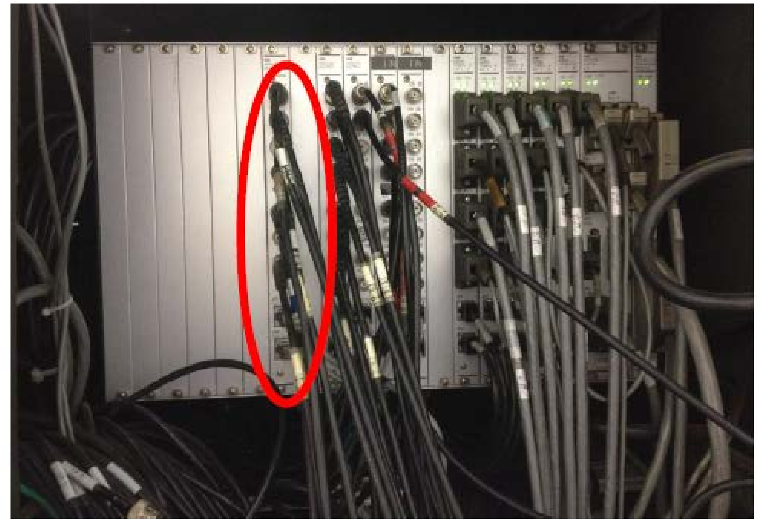
Glitches in signals from SRMD



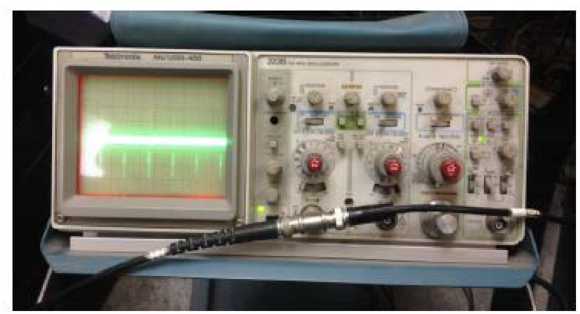
Routing of cables



Gray Cables in second picture go to the back.

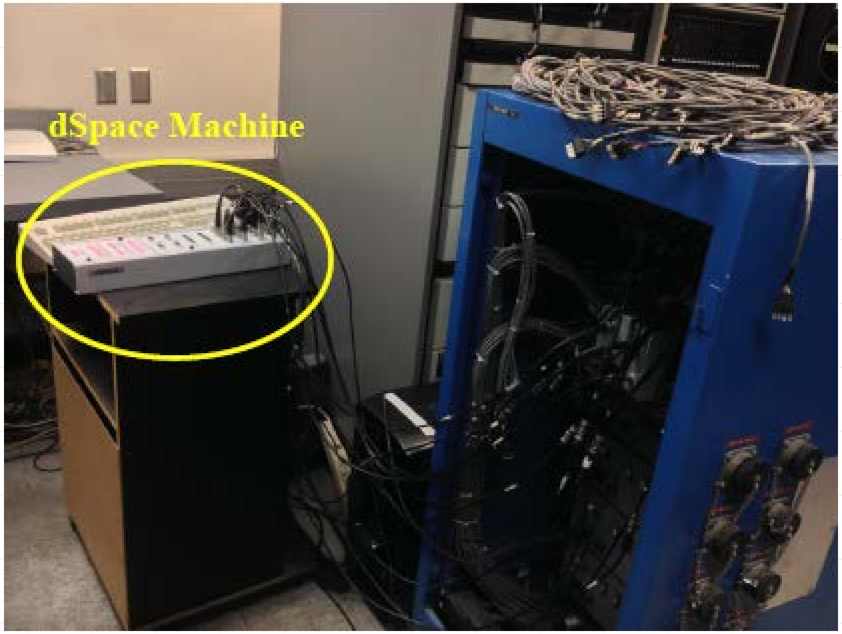


Feedbacks are coming from controller were connected to oscilloscope through BNC cables. Figure below shows the glitches that were observed.

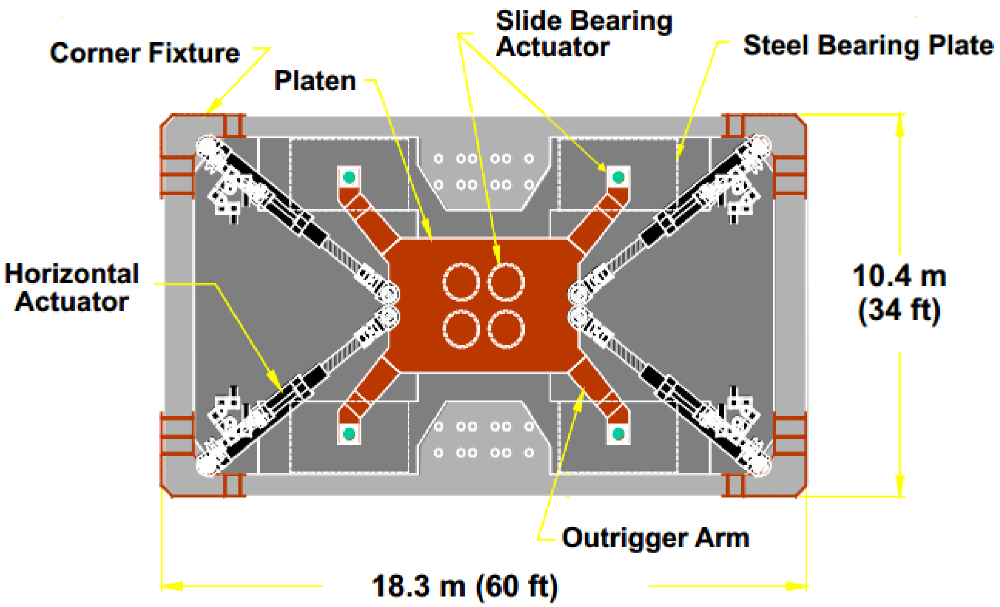


In order to filter these glitches, conditioner was added before sending the signal to dSpace controller board. (Real Time Machine)

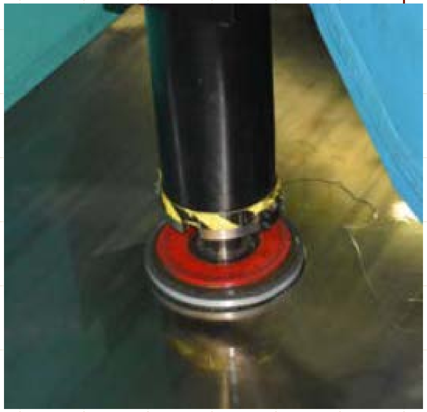
Use signal conditioner to filter

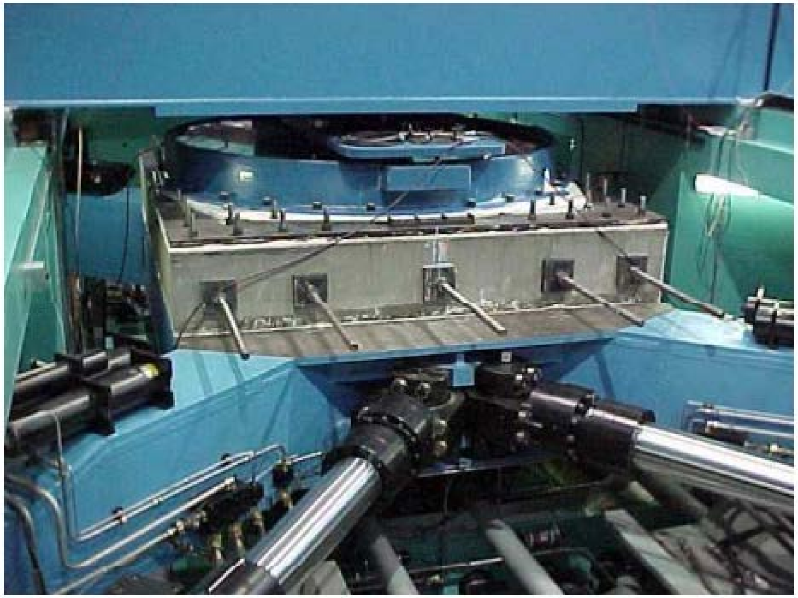


Friction in SRMD sliding surfaces



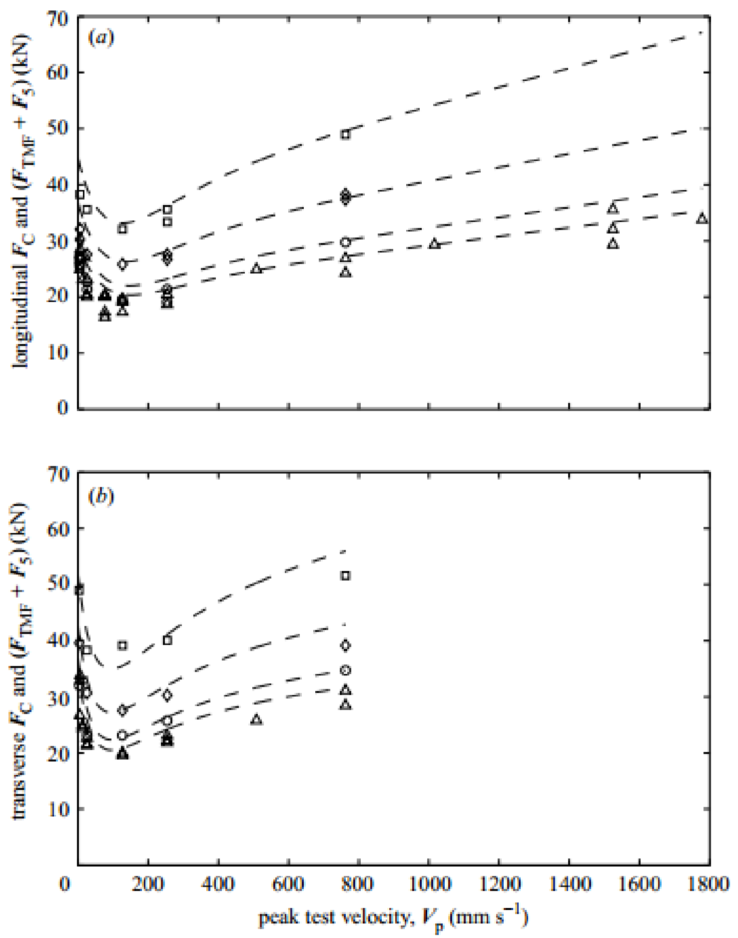
Plan View of Test System

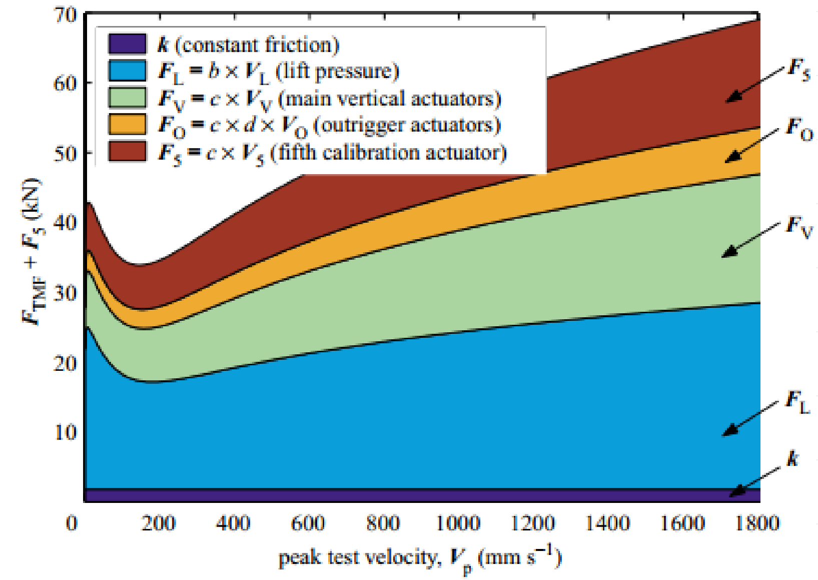




Previous Studies

✦ SRMD Machine





$$(\boldsymbol{F}_{\mathrm{TMF}} + \boldsymbol{F}_5) = \boldsymbol{k} + \boldsymbol{b}(\boldsymbol{V}_{\mathrm{L}}) + \boldsymbol{c}(\boldsymbol{V}_{\mathrm{V}}) + \boldsymbol{cd}(\boldsymbol{V}_{\mathrm{O}}) + \boldsymbol{c}(\boldsymbol{V}_5), \tag{4.3}$$

where $\boldsymbol{F}_{\mathrm{TMF}} + \boldsymbol{F}_5$ is the sum of the theoretical machine friction force and the friction force in the fifth calibration bearing; $\boldsymbol{k}$ is a constant friction force;

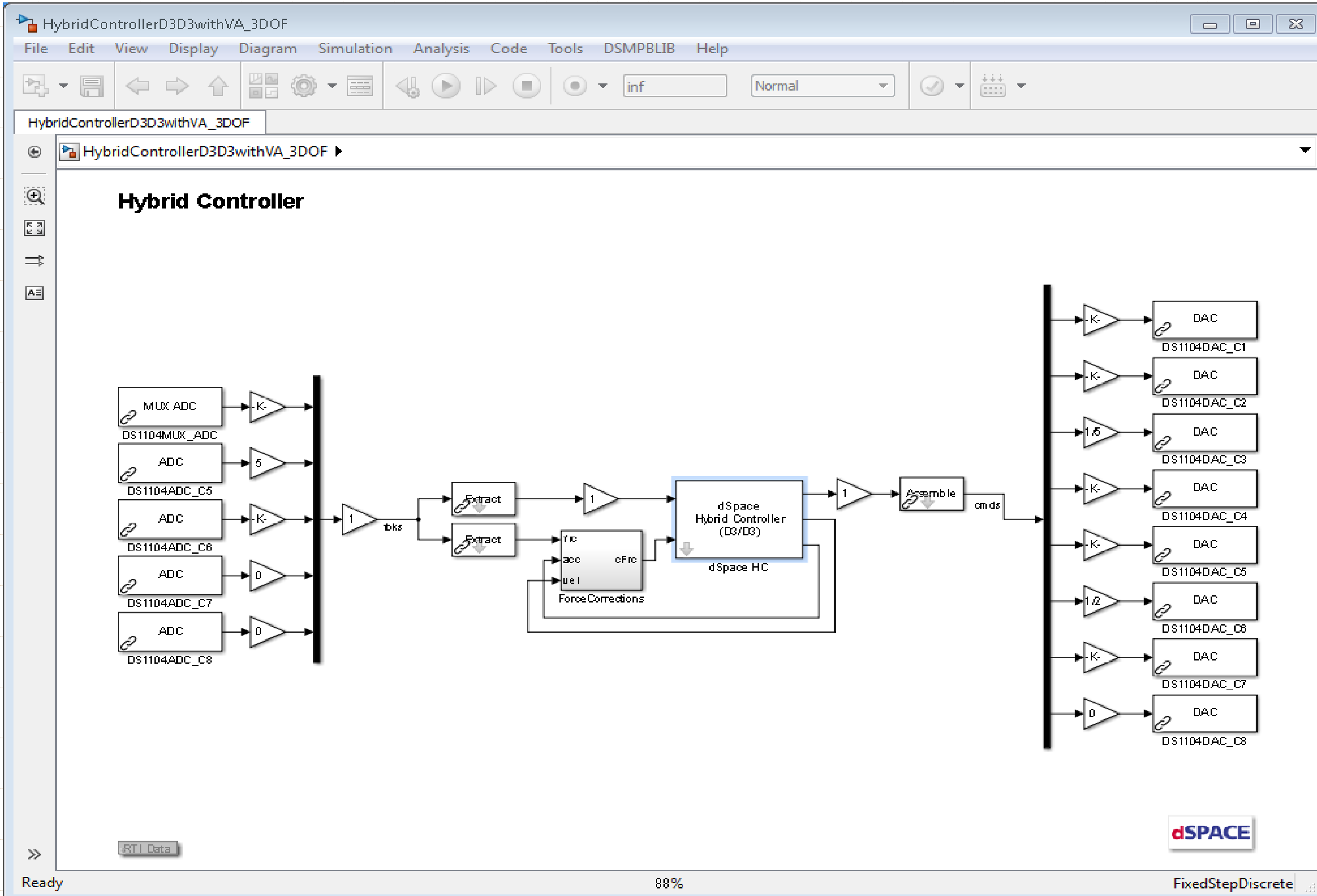
$$\boldsymbol{b} = \boldsymbol{b}_1(\boldsymbol{b}_2^{\boldsymbol{V}_{\mathrm{P}}}) - \boldsymbol{b}_3(\boldsymbol{b}_4^{\boldsymbol{V}_{\mathrm{P}}}) + \boldsymbol{b}_5(\boldsymbol{V}_{\mathrm{p}}) + \boldsymbol{b}_6,$$

$$\boldsymbol{c} = \boldsymbol{c}_1(\boldsymbol{c}_2^{\boldsymbol{V}_{\mathrm{P}}}) - \boldsymbol{c}_3(\boldsymbol{c}_4^{\boldsymbol{V}_{\mathrm{P}}}) + \boldsymbol{c}_5(\boldsymbol{V}_{\mathrm{p}}) + \boldsymbol{c}_6,$$

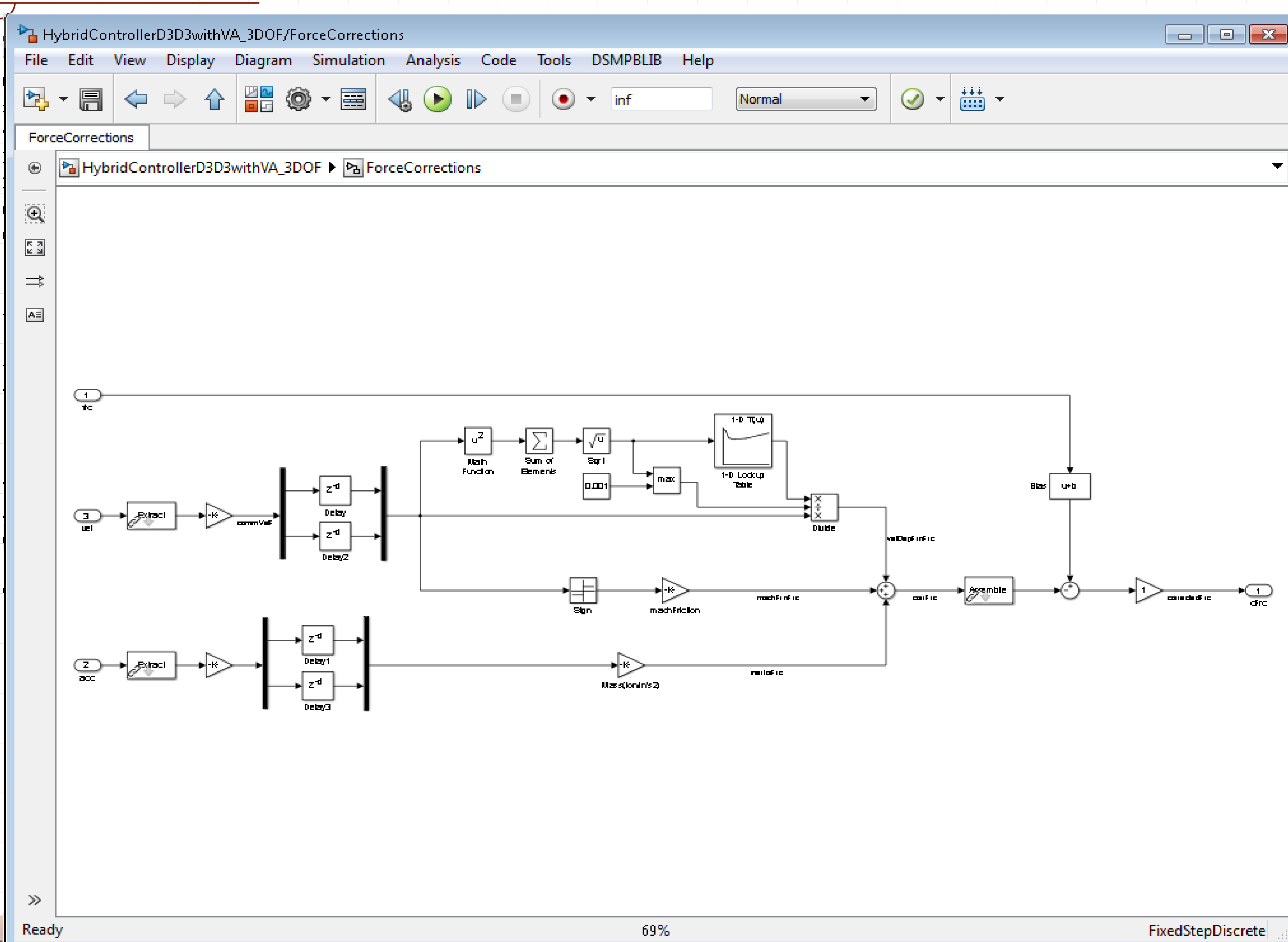
$$\boldsymbol{d} = \frac{\text{piston area of vertical actuators}}{\text{piston area of outrigger actuators}} = 14;$$

$\boldsymbol{V}_{\mathrm{p}}$ is the peak test velocity; $\boldsymbol{V}_{\mathrm{L}}$ is the total vertical 'lift pressure' force at all actuators; $\boldsymbol{V}_{\mathrm{V}}$ is the total vertical force on the main vertical actuators; $\boldsymbol{V}_{\mathrm{O}}$ is the total vertical force on the outrigger actuators; $\boldsymbol{V}_5$ is the total vertical force on the fifth calibration bearing; and $\boldsymbol{k}$, $\boldsymbol{b}$, $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_6$, $\boldsymbol{c}_1, \ldots, \boldsymbol{c}_6$, $\boldsymbol{d}$ are the empirical coefficients to fit the test data.

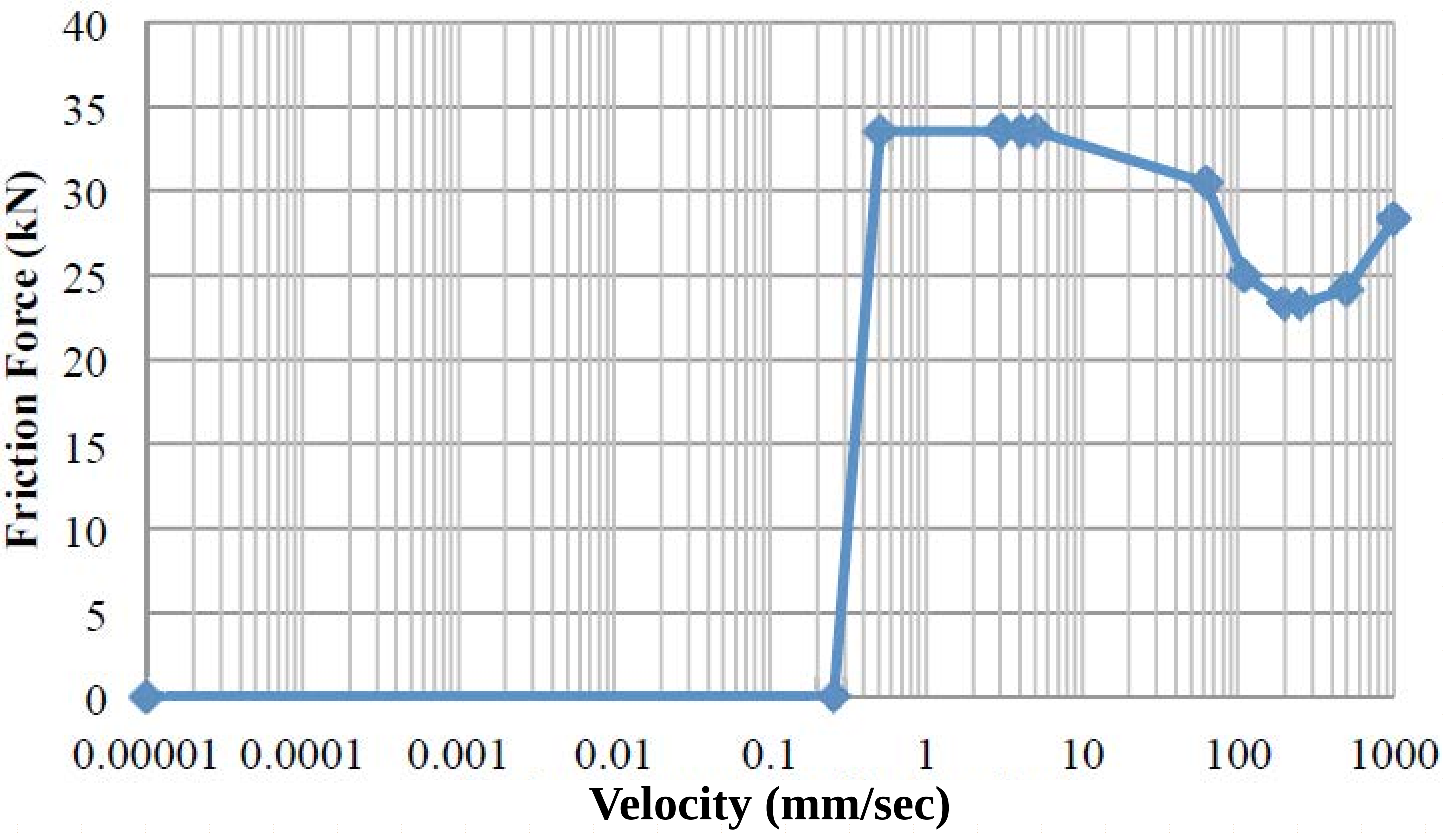
Friction correction in Simulink model



Friction correction in Simulink model



Friction correction in Simulink model



Acknowledgments

These findings summarizes information developed as part of the overall research project entitled “Seismic Isolation of Nuclear Power Plants (Phase 2).” This work was supported by contract KCN04-12-96 from KEPCO Engineering and Construction Company, Inc. to the Pacific Earthquake Engineering Research Center (PEER). The overall research program was supported by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) with financial resources provided by the Ministry of Trade, Industry & Energy, Republic of Korean (through grant No. 2011151010010A).

Questions?
Thank you!

http://openfresco.berkeley.edu/

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